PB-241 768

# A REVIEW OF CONTROL STRATEGIES FOR IN-USE VEHICLES

J. Meltzer, et al

Aerospace Corporation

Prepared for:

Environmental Protection Agency

December 1974

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## TECHNICAL REPORT DATA
*(Please read Instructions on the reverse before completing)*

1. REPORT NO.
EPA-460/3-74-021

2.

PB 241 768

4. TITLE AND SUBTITLE
A REVIEW OF CONTROL STRATEGIES
FOR IN-USE VEHICLES

5. REPORT DATE
December 1974

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
J. Meltzer, M.G. Hinton, T. Iura, A. Burke,
L. Forrest, W.M. Smalley, F. Augustine

8. PERFORMING ORGANIZATION REPORT NO.
ATR-74(7328)-1

9. PERFORMING ORGANIZATION NAME AND ADDRESS
The Environmental Programs Group
Environment and Urban Division
The Aerospace Corporation
El Segundo, California 90245

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.
68-01-0417

12. SPONSORING AGENCY NAME AND ADDRESS
EPA, Office of Air and Waste Management
Office of Mobile Source Air Pollution Control
Division of Emission Control Technology
Ann Arbor, Michigan 48105

13. TYPE OF REPORT AND PERIOD COVERED
Final

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

A review was conducted of studies and evaluations made by the EPA and various State agencies of the technical feasibility, emission reduction effectiveness, and costs associated with implementing various approaches for reducing the emission of air pollutants from automobiles currently in use. These approaches include: inspection/maintenance programs, retrofit programs, and the conversion of in-use vehicles to permit the use of gaseous fuels. The emphasis of this report is on providing emission reduction and cost data that may be useful to the States in evaluating the alternative approaches to in-use vehicle emission control, as those approaches may be applied to their particular air quality requirements. This report is supplementary to previous EPA publications covering these same topical areas.

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17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| Air pollution | Air pollution control | |
| In-use vehicles | Mobile sources | |
| Inspection/maintenance | Emissions | |
| Retrofit | Costs | |
| Gaseous fuel conversion | Cost effectiveness | |

| | | |
|---|---|---|
| 18. DISTRIBUTION STATEMENT<br>Unlimited | 19. SECURITY CLASS *(This Report)*<br>UNCLASSIFIED | 21. NO. OF PAGES<br>236 |
| | 20. SECURITY CLASS *(This page)*<br>UNCLASSIFIED | 22. PRICE<br>$7.50/2.25 |

EPA Form 2220-1 (9-73)

EPA-460/3-74-021

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by

The Environmental Programs Group
The Aerospace Corporation
and
The Emission Control Technology Division
U.S. Environmental Protection Agency

Contract No. 68-01-0417

EPA Project Officer: F. Peter Hutchins

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
Office of Mobile Source Air Pollution Control
Emission Control Technology Division
Ann Arbor, Michigan 48105

December 1974

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Publication No. EPA-460/3-74-021

# FOREWORD

This report, prepared by The Aerospace Corporation for the Environmental Protection Agency (EPA), Division of Emission Control Technology, presents the results of a review of studies and evaluations made by the EPA and various state agencies of the technical feasibility, emission reduction effectiveness, and costs associated with implementing various approaches for reducing the emission of air pollutants from automobiles currently in use. These approaches include: inspection/maintenance programs, retrofit programs, and the conversion of in-use vehicles to permit the use of gaseous fuels.

All of these control strategy topics were previously addressed by EPA in a 1972 report entitled Control Strategies for In-Use Vehicles.* EPA also provided further guidance to the States in 1973 by publishing estimates of emission reductions that are likely to be achievable through application of inspection, maintenance, and retrofit measures for in-use light duty motor vehicles.**

Since the preparation and publication of the above-cited EPA reports, there have been continuing EPA and State agency-sponsored programs that have added to the state of knowledge concerning the in-use control strategies for light duty vehicles. Therefore, the present report has been prepared to supplement the above-cited EPA reports by summarizing the more recently acquired data and by presenting cost and cost-effectiveness values for the various in-use control strategy options.

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*U.S. Environmental Protection Agency, Office of Air and Water Programs, Mobile Source Pollution Control Programs, Washington, D.C. 20460 (November 1972).

**"Appendix N - Emissions Reductions Achievable Through Inspection, Maintenance, and Retrofit of Light Duty Vehicles," Federal Register, Vol. 38, No. 110 (Friday, June 8, 1973).

A brief introductory statement and a summary of the major findings are presented in Section 1 of the report. In Section 2, the major aspects of the several approaches available for inspection/maintenance programs, including a detailed discussion of program implementation considerations, are presented. The retrofit of both light and heavy duty vehicles with emission control systems or devices are discussed in Section 3, and the applicability and characteristics of the conversion of in-use vehicles for gaseous fuel operation are examined in Section 4.

# ACKNOWLEDGMENT

Appreciation is acknowledged for the guidance and assistance provided by Mr. F. P. Hutchins of the Environmental Protection Agency, Division of Emission Control Technology, who served as EPA Contract Project Officer for this study. Appreciation is also acknowledged for the various DECT members who reviewed the study progress and provided technical guidance, including Harold Davis and Andrew Kaupert.

The following technical personnel of The Aerospace Corporation made valuable contributions to the review and analyses performed under this contract.

M. G. Hinton
A. Burke
F. Augustine
L. Forrest
W. M. Smalley
T. Iura

Approved by:

J. Meltzer, Group Director
Environmental Programs Group
Directorate

## CONTENTS

FOREWORD . . . . . . . . . . iii

ACKNOWLEDGMENTS . . . . . . . . . . v

1. OVERVIEW . . . . . . . . . . 1-1

- 1.1 Introduction . . . . . . . . . . 1-1
- 1.2 Summary of Major Findings . . . . . . . . . . 1-4

REFERENCES . . . . . . . . . . 1-23

2. EMISSION INSPECTION AND MAINTENANCE APPROACHES . . . . . . . . . . 2-1

- 2.1 Introduction . . . . . . . . . . 2-1
  - 2.1.1 Types of I/M Approaches . . . . . . . . . . 2-1
  - 2.1.2 Criteria for Evaluation of I/M Approaches . . . . . . . . . . 2-2
- 2.2 Emission Inspection Procedures . . . . . . . . . . 2-6
  - 2.2.1 Alternative Short Emission Test Procedures . . . . . . . . . . 2-6
  - 2.2.2 Relatability and Discrimination Characteristics of Short Emission Test Procedures . . . . . . . . . . 2-8
- 2.3 Alternative Maintenance Procedures . . . . . . . . . . 2-16
  - 2.3.1 Engine and Emission Control System Diagnostic and Parameter Tests and the Sensitivity of Emissions to Particular Malfunctions . . . . . . . . . . 2-18
  - 2.3.2 Maintenance Phase Tune-up/Repair Procedures . . . . . . . . . . 2-29
- 2.4 Emission Reductions and Repair Costs of Alternative I/M Approaches . . . . . . . . . . 2-37
  - 2.4.1 Emission Reductions Obtained Using Alternative I/M Approaches . . . . . . . . . . 2-37
  - 2.4.2 Repair Costs for Serviced Vehicles . . . . . . . . . . 2-43

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CONTENTS (Continued)

2.5 Deterioration of Emissions With and Without Periodic I/M . . . . . 2-46

2.5.1 Deterioration of Emissions with Voluntary Maintenance . . . . . 2-47

2.5.2 Effective Emission Reductions Resulting from I/M Programs . . . . . 2-47

2.6 Cost Effectiveness of Alternative I/M Approaches . . . 2-54

2.6.1 Cost Effectiveness Criteria . . . . . 2-54

2.6.2 I/M Program Costs . . . . . 2-55

2.6.3 Comparison of the Cost Effectiveness of Various I/M Approaches . . . . . 2-58

2.7 I/M Program Implementation Considerations . . . . . 2-64

2.7.1 Initial Planning and Tradeoff Studies . . . . . 2-64

2.7.2 Development and Passage of Enabling Legislation . . . . . 2-90

2.7.3 Engineering and Administrative Studies . . . . 2-93

2.7.4 Pilot Program Construction and Procurement . . . . . 2-94

2.7.5 Pilot Program Operation . . . . . 2-94

2.7.6 Planning for Full-Scale Program . . . . . 2-95

2.7.7 Full-Scale Program Construction and Procurement . . . . . 2-96

2.7.8 Full-Scale Program Operation . . . . . 2-96

2.7.9 Ongoing Licensing and Quality Control Program . . . . . 2-96

2.8 I/M of Heavy Duty Vehicles . . . . . 2-97

REFERENCES . . . . . 2-112

3. RETROFIT OF EMISSION CONTROL SYSTEMS/DEVICES FOR IN-USE VEHICLES . . . . . 3-1

3.1 Introduction . . . . . 3-1

CONTENTS (Continued)

3.1.1 Control of Exhaust Emissions .......... 3-1
3.1.2 Control of Crankcase Emissions ......... 3-1
3.1.3 Control of Evaporative Emissions ........ 3-3
3.1.4 Criteria for Evaluation of Retrofit Emission Control Systems/Devices .......... 3-3
3.2 Evaluation of Retrofit Emission Control Systems .... 3-5
3.2.1 Exhaust Emission Control ............. 3-5
3.2.2 Crankcase Emissions ................ 3-34
3.2.3 Evaporative Emissions ............... 3-35
3.3 Implementation of Retrofit Strategies for Light Duty Vehicles .......................... 3-39
3.3.1 Introduction ..................... 3-39
3.3.2 Selection and Certification ............. 3-39
3.3.3 Cost and Financing .................. 3-40
3.3.4 Implementation Scheduling ............. 3-40
3.4 Retrofit Emission Control for Trucks ........... 3-42
3.4.1 General Considerations ............... 3-42
3.4.2 Retrofit of Gasoline-Fueled Trucks ....... 3-45
3.4.3 Retrofit of Diesel Powered Trucks ....... 3-57
3.4.4 Implementation of Retrofit Programs for Trucks ....................... 3-59
REFERENCES ............................... 3-62
4. CONVERSION OF IN-USE VEHICLES FOR GASEOUS FUEL OPERATION ......................... 4-1
4.1 Introduction ......................... 4-1
4.2 Description of Gaseous Fuel Systems ........... 4-2
4.3 Emission Reductions Attainable through Gaseous Fuel Conversion ..................... 4-6
4.4 Initial and Operating Costs .................. 4-9

CONTENTS (Continued)

4.5 Cost Effectiveness of Emission Reduction through Conversion to Gaseous Fuels . . . . . . . . . . . . . . . . . . . 4-12
4.6 Other Aspects of Gaseous Fuel Conversion . . . . . . . . . 4-14
4.7 Usefulness of Gaseous Fuel Conversion as an In-Use Vehicle Emission Control Strategy . . . . . . . . . 4-15
REFERENCES . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 4-19

## FIGURES

2-1. Speed and Time Characteristics of Short Urban Cycles . . . . . 2-11

2-2. Typical Key Mode Report Card . . . . . . . . . . . . . . . . . . . . . 2-35

2-3. Hydrocarbon Levels vs Population Percentage . . . . . . . . . . 2-40

2-4. Carbon Monoxide Levels vs Population Percentage . . . . . . . 2-41

2-5. Emission Reduction Effectiveness as a Function of Rejection Rate . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2-42

2-6. Average Vehicle Repair Cost . . . . . . . . . . . . . . . . . . . . . . 2-44

2-7. Effect of Maintenance on Emission Deterioration with Vehicle Age . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2-48

2-8. Key Mode Double-Lane Configuration and Mobile Test Facility . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2-73

2-9. Estimated Time Required for Implementation of State-Owned Inspection Lanes Using Idle or Loaded Mode Tests . . . 2-91

2-10. Variation of Emission Levels with Inertia Test Weight . . . . . 2-101

2-11. Vehicles in Fleets of 10 or More . . . . . . . . . . . . . . . . . . . 2-108

3-1. Typical Spark Ignition Engine Exhaust Emission vs Air/Fuel Ratio (Gasoline) . . . . . . . . . . . . . . . . . . . . . . . 3-25

3-2. Location of Evaporative Control System Components . . . . . . 3-37

4-1. Schematic Diagram for Dual Fuel Operation with LPG and Gasoline . . . . . . . . . . . . . . . . . . . . . . . . . 4-3

## TABLES

1-1. Summary of In-Use Vehicle Emission Control Strategies Proposed in State Implementation Plans (January 1974) .... 1-3

1-2. Summary of Typical Emission Reductions and Repair Costs for Various Rejection Rates and I/M Strategies ..... 1-8

1-3. Comparison of the Cost Effectiveness of Various I/M Approaches .............................. 1-9

1-4. Major Steps Involved in Implementation of I/M Program .......................... 1-11

1-5. Maximum Emission Reductions and Fuel Penalty for Various Retrofit Strategies on Vehicles of Differing GVW .................................. 1-13

1-6. The Cost Effectiveness of Various Retrofit Strategies on Vehicles of Differing GVW .................. 1-14

1-7. Emission Levels and Reductions Obtainable Through Single-Fuel Gaseous Conversion ................... 1-17

1-8. Summary of Cost Effectiveness Information for Gaseous Fuel Conversion ........................... 1-19

1-9. Comparison of the Emission Reduction Potential and Cost Effectiveness of In-Use Vehicle Control Strategies (Light Duty Vehicles) ........................ 1-21

2-1. Summary of Major Features of I/M Studies Conducted to Date ................................. 2-4

2-2. Characteristics of Short Test Procedures for Emission Inspection ............................... 2-9

2-3. Load and Speed Conditions for the Key Mode Test ........ 2-10

2-4. Advantages and Disadvantages of the Unloaded Idle Test Procedure ............................. 2-10

2-5. Advantages and Disadvantages of Key Mode Test Procedure ............................. 2-12

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TABLES (Continued)

2-6. Advantages and Disadvantages of Various Loaded Short Urban Test Cycles . . . . . . . . . . . . . . . . . . . . . . . . 2-13

2-7. Maintenance Approaches in Various I/M Strategies . . . . . . . 2-17

2-8. Summary of Engine and Emission Control System Diagnostic Tests and Associated Equipment/Instruments . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2-21

2-9. Effect on Emissions of Various Engine/Emission Control System Component Malfunctions/Maladjustments . . . . . . . . . 2-23

2-10. The Quantitative Effect of Minor Engine/Emission Control System Malfunctions/Maladjustments on Emissions . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2-25

2-11. The Effect of Major Engine Malfunctions on Emissions . . . . . 2-27

2-12. The Effect of Major Emission Control System Failures on Emissions . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2-28

2-13. Emission and Engine Parameter Distributions for Two Vehicle Fleets . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2-30

2-14. Parts Replaced During Minimum Pollution Capability Tune-Ups . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2-31

2-15. EPA Estimated Emission Reductions for I/M Programs . . . . 2-53

2-16. Emission Inspection Lane Costs . . . . . . . . . . . . . . . . . . 2-56

2-17. Inspection Lane Utilization Data . . . . . . . . . . . . . . . . . . 2-57

2-18. Fuel Economy Changes of Repaired Vehicles . . . . . . . . . . . 2-59

2-19. Summary of I/M Emission Reduction and Cost Effectiveness for Idle Emission Test/Repair and Mandatory Maintenance . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2-61

2-20. Summary of the I/M Emission Reduction and Cost Effectiveness for Key Mode Emission Test/Repair Procedures . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2-62

TABLES (Continued)

2-21. Major Steps Involved in Implementation of I/M Program . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2-65

2-22. New Jersey-Approved Manufacturers of Low Cost Infrared Analyzers Suitable for Use in Repair Garages . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2-72

2-23. Percent (National Averages) of In-Use Trucks in Various Weight Classes . . . . . . . . . . . . . . . . . . . . . . . . . . 2-98

2-24. Federal Emission Standards for Heavy Duty Engines . . . . . . 2-99

2-25. Surveillance Study of Heavy Duty Engine Emissions Over 12 Months . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2-104

2-26. Maintenance of Trucks and Other Heavy Duty Vehicles . . . . . 2-106

3-1. Light Duty Vehicle Emission Control Requirements . . . . . . . 3-2

3-2. Estimated Emission Reductions for Retrofit of Light Duty Vehicles . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 3-6

3-3. Emission Reduction from As-Received Baseline . . . . . . . . . 3-8

3-4. Emission Reduction from Tuned Baseline . . . . . . . . . . . . . 3-8

3-5. Emission Test Results, 1972 CVS Cold Start California Fleet . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 3-18

3-6. Rebaselined Emissions, California Fleet (June 1974) . . . . . . 3-19

3-7. Oxidation Catalyst and EGR Systems . . . . . . . . . . . . . . . . 3-23

3-8. Emission Changes at Altitude (Denver, Colorado) . . . . . . . . 3-26

3-9. Retrofit Emission Control at High Altitude . . . . . . . . . . . . 3-28

3-10. Cost Effectiveness Summary, Light Duty Vehicles HC Emission Reductions . . . . . . . . . . . . . . . . . . . . . . . . . . 3-31

3-11. Cost Effectiveness Summary, Light Duty Vehicles CO Emission Reductions . . . . . . . . . . . . . . . . . . . . . . . . . . 3-32

TABLES (Continued)

3-12. Cost Effectiveness Summary, Light Duty Vehicles $NO_x$ Emission Reductions . . . . . 3-33

3-13. Emission Values for Medium Duty Vehicles by Model Year . . . . . 3-44

3-14. Group Representative Vehicle-Engine Combinations (Emission Control Devices - 1973 Models) . . . . . 3-46

3-15. Experimental 23-Mode Emissions Test Schedule (Heavy Duty Gasoline Engines) . . . . . 3-49

3-16. Summary of Emission Reductions at Various Steady-State Operating Conditions Using Retrofitted Catalyst and EGR Systems . . . . . 3-50

3-17. Summary of SWRI Heavy Duty Engine Retrofit Data . . . . . 3-51

3-18. Estimated Emission Reductions for Retrofit of the 6000 to 10,000 GVW Class . . . . . 3-52

3-19. Estimated Emission Reduction and Fuel Penalty Characteristics of Retrofit Emission Control Systems for Trucks . . . . . 3-54

3-20. Estimated Cost Effectiveness of Various Retrofit Strategies for Gasoline-Fueled Trucks . . . . . 3-56

3-21. Comparison of the Estimated Cost Effectiveness of Various Retrofit Strategies on Vehicles of Differing GVW . . . . . 3-58

3-22. Summary of Diesel Engine Emission Reductions Using Various Retrofit Approaches . . . . . 3-60

4-1. Properties of Gasoline and Gaseous Fuel Alternatives . . . . . 4-4

4-2. Tankage and Range Comparisons . . . . . 4-5

4-3. Emission Levels and Reductions Obtainable Through Single-Fuel Gaseous Conversion . . . . . 4-8

TABLES (Continued)

4-4. Initial Costs for Conversion to Gaseous Fuels . . . . . . . . . . . 4-10

4-5. Fuel Cost and Fuel Economy Data for Gaseous Fuel Operation . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 4-10

4-6. Summary of Cost Effectiveness Information for Gaseous Fuel Conversion . . . . . . . . . . . . . . . . . . . . . . . . . . . . 4-13

# 1. OVERVIEW

## 1.1 INTRODUCTION

### 1.1.1 Background

The Clean Air Act (Ref. 1-1) provides two basic strategies for controlling air pollutant emissions from motor vehicles. The United States Environmental Protection Agency is empowered to promulgate and enforce emission standards applicable to new motor vehicles; this has been done on an increasingly stringent basis since the 1968 model year. The States are responsible for the establishment and enforcement of emission control strategies that apply to vehicles in use, to the extent that limitations on vehicular emissions beyond those resulting from the Federal new vehicle standards are necessary for each State to achieve and maintain the National Ambient Air Quality Standards.

In preparing their implementation plans for the achievement of the air quality standards, a substantial number of States have determined that the application of control strategies to in-use vehicles will be necessary if the objectives of the Clean Air Act are to be achieved. A number of alternatives are potentially available to the States to control emissions from in-use vehicles. These include programs of (1) periodic inspection and maintenance of vehicles to minimize excessive emissions that result from inadequate or improper vehicle maintenance; (2) the retrofitting of emission control systems to vehicles not originally so equipped, or the installation of more effective emission control systems on vehicles already controlled; (3) the conversion of motor vehicles to permit their operation using gaseous fuels; (4) the control of gasoline marketing hydrocarbon emissions; (5) restrictions on the use and parking of vehicles and modification of traffic flow patterns; (6) improvements and expansion of public transportation systems together with incentives or restrictions to ensure the more extensive use of those systems in place of private vehicles; (7) modification of social patterns that influence transportation patterns, such as work schedules; and (8) restrictions on land use to influence transportation needs and patterns.

The first four approaches either depend on the application of emission control to the operation of individual vehicles without necessarily altering the mode or frequency of use of those vehicles or on the control of emissions from the gasoline marketing operations that service these vehicles; these may be referred to as "hardware" approaches. In contrast, the other approaches seek to modify vehicle usage patterns without altering the emissions characteristics of the individual vehicles and can be seen to be complementary to the hardware approaches. A summary of the hardware type in-use vehicle emission control strategies that have been included in the State implementation plans (as of January 1974) for various cities and Air Quality Control Regions (AQCRs) is given in Table 1-1.

### 1.1.2 Scope

This report deals with three hardware approaches to in-use vehicle emission control, namely, inspection/maintenance programs, retrofit programs, and the conversion of vehicles to permit the use of gaseous fuels. The non-hardware approaches are discussed in other reports (Refs. 1-2 through 1-5). This report presents the major results of recent studies and evaluations made by EPA and various State agencies of the feasibility, emission reduction effectiveness, and costs of these hardware approaches to in-use vehicle emission control. Thus, it supercedes previous EPA publications covering these same topical areas (Refs. 1-6 and 1-7).

In general, the emphasis of this report is on providing emission reduction and cost data that may be useful to the States in evaluating the alternative approaches to in-use vehicle emission control, as those approaches may be applied to their particular air quality requirements. No attempt has been made to identify a "best" in-use vehicle emission control approach or an optimum combination of approaches. Such evaluations must be performed on a region-by-region basis, taking account of the time period

Table 1-1. Summary of In-Use Vehicle Emission Control Strategies Proposed in State Implementation Plans (January 1974)[a]

| City/AQCR | Inspection/ Maintenance | | Retrofit Emission Control | | | | Gasoline Vapor Recovery[d] |
|---|---|---|---|---|---|---|---|
| | LDV[b] | HDV[c] | Air Bleed | $NO_x$ Control | Oxid. Catalyst | HDV Included[c] | |
| Boston | L[e] | L | X[f] | X | X | X | X |
| Springfield | L | L | | | | | |
| NJ, NY, Conn. | I[g] | I | X | | X | X | X |
| Philadelphia | I | | X | | X | | X |
| Baltimore | L | L | X | X | X | X | X |
| Pittsburgh | I | I | X | | | | X |
| Nat. Capital Area | L | L | X | X | X | X | X |
| Chicago | I | | | | X<br>(taxis) | | |
| Indianapolis | I | | | | | | X |
| Cincinnati | I | | | | | | |
| Houston | I | | | X | | | X |
| Dallas, Ft. Worth | | | | | | | X |
| San Antonio | I | | | | | | X |
| Denver | I | | | | X | | X |
| Salt Lake City | I | | X | | | | |
| Phoenix, Tucson | X | X | X | | X | | X |
| San Francisco | L | | | X | X | | |
| Los Angeles | L | | | X | X | | X |
| San Diego | L | | | X | X | | |
| Sacramento | L | | | X | X | | X |
| San Joaquin | L | | | X | X | | X |
| Portland | I | | X | | X | | |
| Fairbanks | I | I | X | | X | | |
| Seattle | I | I | X | | | | |
| Spokane | I | | X | | | | |

[a] This table is extracted from EPA document No. EPA-450/2-74-004, dated April 1974. This document is continually updated and should be referred to for changes to those strategies shown here

[b] Light duty vehicles (GVW ≤ 6000 lb)

[c] Heavy duty vehicles (GVW > 6000 lb). In most cases, only medium duty vehicles (MDV < 10,000 lb) are included.

[d] A 90-percent vapor recovery required

[e] Loaded emissions test = L

[f] Applicable = X

[g] Idle emissions test = I

over which emission reductions must be achieved and the magnitudes of the needed reductions, and using vehicle population data representative of the area under consideration.

### 1.1.3 Organization of the Report

This report is organized into four major sections. In Sections 2 through 4, the subjects covered deal, respectively, with inspection/maintenance programs, retrofit emission control programs, and gaseous fuel conversion. The sections on inspection/maintenance and retrofit programs include consideration of both light and heavy duty vehicles. High altitude effects on retrofit device/system performance are also included. Each of the major sections provides a detailed review of available information relating to a particular emission control strategy for in-use vehicles. Cost effectiveness, planning, and implementation considerations are included in the discussion on each control strategy. The major findings in each topical area are highlighted in the following section, together with a comparison of the emission reduction potential and cost effectiveness of the various hardware-type control strategies for in-use vehicles.

## 1.2 SUMMARY OF MAJOR FINDINGS

In all cases, quoted emissions reductions or changes are either on the basis of the 1972 or the 1975 Federal Test Procedure (FTP) and are not to be confused with results that would be obtained by other test procedures.

### 1.2.1 Inspection/Maintenance

Inspection/maintenance (I/M) programs reduce emissions from in-use vehicles through ensuring that the emission levels of those vehicles are not permitted to deteriorate, through inadequate or improper maintenance, substantially beyond the levels of which the vehicles were capable when new. The I/M programs can accomplish emission reductions only to the extent that voluntary maintenance is inadequate in maintaining the engines and emission control systems in good operating condition. However, voluntary maintenance is often not done on a regular basis, is not normally directed toward emission control, and does not result in minimizing exhaust emissions.

Studies conducted using representative fleets of privately owned in-use automobiles (light duty vehicles) have demonstrated that significant reductions in the aggregate emissions of those groups of vehicles can be obtained through more frequent engine maintenance than is presently practiced. It has been found that over half of the vehicles in a typical fleet had malfunctions or maladjustments that, when corrected, resulted in a decrease in emissions. When maintenance was performed on those vehicles, the average initial reductions in emissions for the entire fleet (including the vehicles not maintained) ranged up to 40 percent for exhaust hydrocarbons (HC) and up to 35 percent for carbon monoxide (CO). Of course, with continued in-service use, both the repaired and nonrepaired vehicles experienced an increase in emissions after the initial I/M period. The vehicles included in the I/M studies did not have nitrogen oxides ($NO_x$) emission control and, consequently, the reductions in the HC and CO emissions were accompanied by a small increase (less than 10 percent) in $NO_x$ emissions. In general, the I/M study results lead to the conclusion that current voluntary maintenance practices are inadequate to keep the emissions of the in-use vehicle population at the minimum levels of which they are capable and, therefore, that implementation of a mandatory I/M strategy could result in significant reductions in HC and CO emissions.

The average emission reductions that can be achieved in a given year from an I/M program depend on the emission reductions of the repaired vehicle immediately after servicing and the rate and extent of deterioration in emissions of both the passed and repaired vehicles prior to the next emissions inspection and/or service period. Considerable information on the emission reductions that can be achieved by repair/maintenance is available, but data on the deterioration of both passed and repaired vehicles are quite limited. Because of this lack of deterioration data, EPA currently utilizes a linear deterioration method, in which it is assumed that the emissions of all serviced vehicles (voluntary and mandatory) deteriorate in a linear manner back to the same level they had before servicing. The effective emission reduction (averaged over a one-year period between inspections and/or servicing) is then one-half of the average fleet emission reduction achieved immediately after repair of the rejected or serviced vehicles. The actual value of emission reduction achieved also depends, of course, on the failure criteria used (pass/fail emission levels) and the resultant rejection rates (percentage of inspected vehicles that fail the emission inspection) that are incorporated into the I/M program.[*] As the number of vehicles rejected increases (i.e., require maintenance), the potential for emission reduction also increases. However, the rate of reduction with increasing failure rate is not linear, with the trend being one of smaller and smaller emissions reductions with each incremental increase in rejection rate. Rejection rates of 100 percent often result in higher emissions levels for the total vehicle population than occur at much lower rejection rates due to the ineffective maintenance being performed on many vehicles. It is advantageous if the emission test procedure utilized can minimize the number of vehicles rejected having relatively low emissions (as measured by the FTP) and the number of vehicles passed having relatively high emissions (as measured by the FTP). Both types of errors tend to reduce the emission reduction that can be achieved by the I/M program.

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[*] As used in this discussion, the term "reject rate" refers to the fraction of inspected vehicles that fail the initial inspection cycle. Repeated reductions in the failure criteria for the purpose of maintaining constant reject rates during subsequent inspection cycles is not only unnecessary but undersirable in most cases.

The emission reduction effectiveness of several alternative approaches to I/M have been evaluated. These included (1) emission inspection (testing) at idle only, followed by repair procedures developed to use idle test results; (2) emission inspection (testing) using a loaded test cycle (Key Mode), followed by repair procedures developed to use Key Mode test results; (3) engine parameter diagnostic inspection and repair; and (4) mandatory maintenance of specified emission-related engine and emission control system components, which is done regularly without prior testing. A summary of the emission reductions and associated repair costs for the inspection repair and mandatory maintenance strategies are given in Table 1-2. The results shown are typical of those that can be achieved by mechanics familiar with emission-reduction-oriented repair procedures. The emission reduction and cost effectiveness of the idle, Key Mode, and mandatory maintenance approaches are given in Table 1-3. In general, the HC and CO emission reductions achieved both increase as the fraction of vehicles receiving mandatory maintenance increases. The cost effectiveness of I/M programs for reducing HC emissions varies in the range $0.25 to $3.67/lb, while the range for CO emissions is $0.04 to $0.32/lb.*

The results given in Table 1-3 indicate that the loaded (Key Mode) test approach yields a greater emission reduction at a correspondingly better cost effectiveness than the idle test approach for both HC and CO emissions. As would be expected, the cost effectiveness of all the I/M approaches is better for uncontrolled than for controlled vehicles. This is primarily due to the fact that uncontrolled vehicles have higher emission levels than controlled vehicles and the percent emission reductions achieved by maintenance are at least as high for the uncontrolled vehicles as for the controlled vehicles. The cost of maintenance does not seem to vary significantly between the two vehicle groups.

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* These values include the effects of an improvement of approximately one percent in the population-averaged fuel consumption. This improvement is the result of increased maintenance on the repaired fraction of the vehicle population.

Table 1-2. Summary of Typical Emission Reductions and Repair Costs for Various Rejection Rates and I/M Strategies

| Rejection Rate (%) | Emission Reduction[a] (%) | | | | Average Repair Cost/ Serviced Vehicles ($) |
|---|---|---|---|---|---|
| | HC | | CO | | |
| | Fleet Average | Serviced Vehicles Only | Fleet Average | Serviced Vehicles Only | |
| **Inspection/Repair Strategy** | | | | | |
| Controlled vehicles[b] | | | | | |
| 10 | 13 | 58 | 12 | 56 | 35.40 |
| 25 | 18 | 41 | 20 | 49 | 34.80 |
| 50 | 20 | 31 | 28 | 41 | 32.50 |
| 100 | 19 | 19 | 29 | 29 | 21.50 |
| Uncontrolled vehicles[c] | | | | | |
| 10 | 23 | 77 | 9 | 49 | 44.00 |
| 25 | 31 | 58 | 17 | 44 | 40.00 |
| 50 | 37 | 50 | 26 | 40 | 34.40 |
| 100 | 38 | 38 | 32 | 32 | 23.70 |
| **Annual Mandatory Maintenance Strategy[d]** | | | | | |
| Controlled vehicles[b] | 14 | | 7 | | 50 to 70 |
| Uncontrolled vehicles[c] | 10 | | 7 | | 50 to 70 |

[a] All emission reductions (1975 CVS-CH FTP) correspond to immediately after servicing.

[b] Light duty controlled vehicles (1968-1971).

[c] Light duty uncontrolled vehicles (pre-1968).

[d] All vehicles are required to undergo prescribed annual maintenance. These emission reductions are based on limited data from an early program. Later results indicate that HC and CO reduction of almost twice these values are achievable with improved servicing.

Table 1-3. Comparison of the Cost Effectiveness of Various I/M Approaches[a]

| | Controlled Vehicles | | | | Uncontrolled Vehicles | | | |
|---|---|---|---|---|---|---|---|---|
| | HC | | CO | | HC | | CO | |
| I/M Strategy | % Reduced[b] | $/lb[c] | % Reduced[b] | $/lb[c] | % Reduced[b] | $/lb[c] | % Reduced[b] | $/lb[c] |
| Idle test | | | | | | | | |
| RR[d] = 20% | 8 | 0.71 | 6 | 0.075 | 8 | 0.35 | 6 | 0.047 |
| RR = 40% | 11 | 0.91 | 9 | 0.088 | 11 | 0.47 | 9 | 0.056 |
| Key Mode test | | | | | | | | |
| RR = 20% | 11 | 0.54 | 7 | 0.067 | 11 | 0.25 | 7 | 0.039 |
| RR = 40% | 14 | 0.72 | 11 | 0.072 | 14 | 0.35 | 11 | 0.044 |
| Mandatory Maintenance | 7 | 6.82 | 5 | 0.77 | 4 | 5.75 | 4 | 0.57 |

[a] Summary of representative data for light duty vehicles.

[b] All emission reductions determined using linear deterioration method.

[c] Cost includes credit for fuel savings.

[d] RR = rejection rate

Various aspects of emission inspection have been investigated as part of recent I/M studies. These studies indicate that several of the short test procedures are adequate for an I/M program in that the procedures, on the average, identify vehicles with relatively high emissions that can be significantly reduced by repair. Available data indicate that the loaded cycle (Key Mode) test procedure is better in this sense than the idle test procedure, and it is expected that the difference in the discrimination capability of the two will be greater as the vehicles to be inspected become more highly emission controlled. However, other factors, such as cost of equipment and facilities, actual emission reductions desired, potential for integration with an on-going safety inspection program, etc., should be considered when selecting the emission inspection approach to be used. Because of the limited available emission surveillance data for heavy duty engines, it is not possible at this time to accurately assess the effect of an I/M program on truck emissions. If subsequent data indicate that the emissions from engines in heavy duty use deteriorate in a manner comparable to those in light duty use, then an I/M program for heavy duty vehicles would be advantageous in those urban areas such as New York and Los Angeles, which have large truck populations.

In selecting which of the I/M approaches is most advantageous for a given State or AQCR and in planning for the timely and effective implementation of the selected I/M strategy, a wide variety of technical, social, and economic factors must be considered and appropriate administrative and legislative decisions made. For example, in Table 1-4, the major steps that would be involved in the eventual implementation of a full-scale I/M program are presented. This delineation of major steps represents the case where a State (or AQCR) has not yet begun or completed initial planning and tradeoff studies, and includes a pilot (or demonstration) program phase prior to implementation of a full-scale I/M program. Each of the major steps of Table 1-4 is discussed in detail in Section 2.7 of this report.

Table 1-4. Major Steps Involved in Implementation of I/M Program

- Initial Planning and Tradeoff Studies
  - Selection of Basic I/M Approach
  - Relationship to Other Existing or Planned Programs
  - Training, Licensing, and Quality Control Aspects
  - Enforcement and Vehicle Owner Requirements
  - Coordination Between Involved Agencies
  - Program Planning and Cost Estimation
- Development and Passage of Enabling Legislation
- Engineering and Administrative Studies
- Pilot Program Construction and Procurement
- Pilot Program Operation
- Planning for Full-Scale Program
- Full-Scale Program Construction and Procurement
  - Recruitment and Training
  - Manpower Development
- Full-Scale Program Operation
- Ongoing Licensing and Quality Control Program
  - Public Information Program

### 1.2.2 Retrofit Emission Control Systems

Retrofit approaches go beyond the attempt made by I/M approaches to keep in-use vehicles at minimum emission levels consistent with their original designs. In a retrofit approach, the goal is to reduce an in-use vehicle's emissions below its "well-maintained" levels through adding new emission control devices or through modifying the original design to achieve lower emissions. The retrofit approach should also be considered a companion program to the I/M approaches. It is necessary to assure that retrofit devices are properly installed, functioning, properly maintained, and retained. An I/M program would make an ideal mechanism to assure the full potential of the retrofit approach is realized. Evaluations of the performance of various retrofit devices or systems on both precontrolled and controlled vehicles have been conducted by EPA and the retrofit hardware manufacturers. Measurements of the effect of the retrofit systems on HC, CO, $NO_x$ emissions and fuel economy have been made for passenger cars and trucks. The evaluation tests in most cases had scatter in the data, which presented difficulty in its interpretation. At present, EPA is in the process of establishing well-defined certification procedures to rectify this situation.

The available retrofit data are presented in Section 3, including best estimates of average emission reductions (percent), associated fuel economy changes, and the cost effectiveness ($/lb) of emission reductions of the various retrofit systems. For each system, the quality and quantity of the data and its statistical characteristics are also discussed. The results of the analysis of the retrofit data are given in Tables 1-5 and 1-6 for those retrofit approaches that appear most likely to be implemented. Results are given for precontrolled and controlled vehicles. Cost effectiveness values are given both including and excluding the effect of fuel economy changes.

For precontrolled light duty vehicles, the CO emissions can be reduced up to 60 percent at zero mileage by the use of an air bleed. This strategy also results in a fuel economy improvement of about 4 percent and a net cost savings over 50,000 miles. HC emissions on precontrolled light duty vehicles can be also reduced by about 20 percent by the use of an air bleed or lean carburetion.

The use of air bleeds or carburetor enleanment are not possible with most post-1970 vehicles as the carburetors are already set as lean as possible without causing misfire and the associated increase in hydrocarbon emissions. For controlled light duty vehicles, the oxidation catalyst with an air pump is an effective means of reducing both CO and HC. By the use of this approach, exhaust emissions of both pollutants can be reduced initially

Table 1-5. Maximum Emission Reductions and Fuel Penalty for Various Retrofit Strategies on Vehicles of Differing GVW

| Retrofit Strategies | Emission Reduction (%)[a] | | | Fuel Penalty[b] (%) |
|---|---|---|---|---|
| | HC | CO | $NO_x$ | |
| Precontrolled vehicles | | | | |
| Air bleed | | | | |
| LDV[c] | 20 | 60 | 0 | -4 |
| Trucks[d] | 15 | 40 | -5 | -4 |
| Lean carburetion + EGR[e] | | | | |
| LDV | 25 | 40 | 50 | 1 |
| Trucks | 10 | 30 | 30 | 0 |
| Controlled vehicles | | | | |
| Oxid. catalyst w/air[f,g] | | | | |
| LDV | 70 | 65 | 10 | 0 |
| Trucks | 80 | 80 | -5 | 0 |
| Oxid. catalyst w/air + EGR | | | | |
| LDV | 70 | 65 | 50 | 3 |
| Trucks | 80 | 80 | 40 | 6 |

[a] Negative sign means increase in emissions

[b] Negative sign means decrease in fuel consumption

[c] Light duty vehicles (GVW ≤ 6000 lb)

[d] Trucks (GVW = 6000 to 10,000 lb)

[e] Exhaust gas recirculation

[f] Air injection for use with catalyst

[g] No catalyst deterioration assumed

Table 1-6. The Cost Effectiveness of Various Retrofit Strategies on Vehicles of Differing GVW

| | Cost Effectiveness ($/lb) | | | | | |
|---|---|---|---|---|---|---|
| | HC | | CO | | $NO_x$ | |
| | LDV[a] | Trucks[b] | LDV | Trucks | LDV | Trucks |
| Precontrolled | | | | | | |
| Lean carburetion | | | | | | |
| Excluding fuel savings | 0.23 | 0.28 | 0.007 | 0.009 | - | - |
| Including fuel savings | +[c] | + | + | + | - | - |
| Lean carburetion + EGR | | | | | | |
| Excluding fuel penalty | 0.24 | 0.84 | 0.010 | 0.024 | 0.53 | 0.34 |
| Including fuel penalty | 0.32 | 0.84 | 0.015 | 0.024 | 0.70 | 0.34 |
| Controlled | | | | | | |
| Oxid. catalyst[d] with air | | | | | | |
| Excluding fuel penalty | 0.62 | 0.45 | 0.05 | 0.039 | 3.6 | - |
| Including fuel penalty | 0.62 | 0.45 | 0.05 | 0.039 | 3.6 | - |
| Oxid. catalyst[d] w/air + EGR | | | | | | |
| Excluding fuel penalty | 0.72 | 0.57 | 0.06 | 0.049 | 0.95 | 0.81 |
| Including fuel penalty | 0.88 | 0.87 | 0.07 | 0.075 | 1.2 | 1.24 |

[a] Light duty vehicles (GVW ≤ 6000 lb)

[b] Trucks (GVW = 6000 to 10,000 lb)

[c] Plus indicates net cost savings; minus indicates retrofit device increased emissions.

[d] No catalyst deterioration included

(before any catalyst deterioration) 65 to 70 percent. Fuel economy is essentially unaffected by the use of the catalyst, but unleaded gasoline is required. The durability of catalysts as retrofit devices is still somewhat in question, but recent advances in catalyst technology make it more likely that satisfactory durability can be achieved in retrofit applications. $NO_x$ emissions can be reduced up to 40 percent on both precontrolled and controlled vehicles, but there is an associated fuel economy penalty of about 5 percent. Combining exhaust gas recirculation (EGR) with air bleed can reduce the fuel penalty to an estimated 1 to 2 percent on uncontrolled cars.

The special case of retrofit emission control at high altitude (e.g., Denver, Colorado) was also reviewed. Substantial differences in emission levels occur at altitude as the result of fuel metering enrichment due to reduced atmospheric pressure at altitude. A number of retrofit emission control systems have been tested in Denver to determine their effectiveness in reducing emissions at altitude. However, only the catalyst systems reduced the emissions at altitude to levels equal to or less than those experienced at sea level. The air bleed devices designed for use at sea level do not permit the addition of sufficient air at altitude to even overcome the effects of reduced ambient density. The limited testing of retrofit devices at altitude indicates that much additional work is needed before such devices will be available to handle this special retrofit situation.

The problem of retrofitting gasoline-fueled vehicles of over 6000 lb gross vehicle weight (GVW) is also considered in Section 3. As indicated by the results given in Tables 1-5 and 1-6, the emission reduction potential (percent) and cost effectiveness of the various retrofit approaches are approximately the same for trucks with GVW ranges between 6000 and 10,000 lb as for light duty vehicles. For heavier vehicles (GVW $>$10,000 lb), however, the situation varies with the retrofit approach being considered. For example, lean carburetion is much less effective for heavy vehicles than for lighter vehicles, because the former operate at high engine loads a greater part of the time. In contrast, oxidation catalyst systems appear equally effective regardless of engine operating load. The fuel penalty associated with spark retard and EGR increases with vehicle weight so that the cost effectiveness of $NO_x$ control on heavy vehicles (GVW > 10,000 lb) is lower than for light vehicles. However, data for retrofit of trucks also is limited, and the above conclusion should be considered preliminary.

### 1.2.3 Conversion for Gaseous Fuel Operation

The modification of in-use vehicles to permit their operation using gaseous fuels falls within the general definition of retrofit approaches. However, the feasibility and/or attractiveness of gaseous fuel conversion as an emission control strategy for in-use vehicles depends not only on the availability, emission reduction effectiveness, and cost of the required hardware but also on a number of other factors, such as the feasibility of providing the necessary supply and fuel distribution system, the cost of the gaseous fuels, and the impact of the diversion of gaseous fuels from other combustion uses. Present and projected supply problems associated with gaseous fuels (propane and natural gas) indicate that this is not a highly viable approach for the reduction of emissions from in-use vehicles. In most previous studies, gaseous fuel conversion was analyzed only in terms of fleet operation (trucks, taxis, etc.), and its attractiveness was based to a large extent on a lower unit cost for the gaseous fuels that would not persist if they were in widespread use for transportation. For that reason, higher unit gaseous fuel costs are used in the present analysis than in most previous studies.

Three basic types of gaseous fuel conversions are of interest: (1) liquefied petroleum gas (LPG - propane), (2) compressed natural gas (CNG-methane), and (3) liquefied natural gas (LNG). Differences among the types manifest themselves principally in such areas as the type of hardware required, conversion and fuel costs, and operating convenience (e.g., tank weight and size, and vehicle range). For example, a typical passenger car fueled with one tankful of gasoline has a range of approximately 300 miles. When limited to the same volume for fuel storage, passenger cars with gaseous fuels would have reduced range capability because of the lower

Table 1-7. Emission Levels and Reductions Obtainable Through Single-Fuel Gaseous Conversion

| Applicable Model Years | Fuel | Emission Levels (1975 FTP) (gm/mi) | | | Percent Reduction From Gasoline Baseline | | |
|---|---|---|---|---|---|---|---|
| | | HC | CO | $NO_x$ | HC | CO | $NO_x$ |
| 1968-1971 | Gasoline (Baseline) | 4.8 | 60.0 | 4.8 | - | - | - |
| | LPG | 2.1 | 14.2 | 2.9 | 55 | 75 | 40 |
| | LNG/CNG | 1.7 | 5.1 | 1.4 | 65 | 90 | 70 |
| 1972-1974 | Gasoline (Baseline) | 2.8 | 30.0 | 3.0 | - | - | - |
| | LPG[a] | 1.5 | 2.7 | 1.1 | 45 | 90 | 60 |
| | LNG/CNG[a] | 1.0 | 2.0 | .7 | 60 | 95 | 70 |

[a] Best attainable, not the average, for 1972-1974 vehicles. In general, emission reductions achievable with dual-fuel systems will be less than those shown.

fuel density. On a comparable basis, LPG would provide a range of 230 miles, CNG 60 miles, and LNG 200 miles.

A significant reduction of all three exhaust pollutants can be attained through conversion from gasoline to gaseous fuel operation (Table 1-7). It should be noted, however, that while the CO emissions are consistently very low (often less than 5 gm/mi), the HC and $NO_x$ emissions vary over a wide range. This variation occurs because the HC and $NO_x$ emissions are very sensitive to ignition timing and air-fuel ratio, with both HC and $NO_x$ decreasing as the engine timing is retarded and the air-fuel ratio is made leaner. Unfortunately, these engine adjustments result in higher fuel consumption and a significant loss in engine horsepower. Hence, depending on the emission standards to be met, different tradeoffs are optimum between emissions, fuel economy, and vehicle performance. For this reason, the emission reductions and levels given in Table 1-7 as being achievable by gaseous fuel conversion should be considered as approximately the best attainable, not the average.

The cost effectiveness of attaining lower emissions through gaseous fuel conversion is summarized in Table 1-8. Comparison of the values ($/lb) shown in the table with those for gasoline retrofit systems indicates that the cost effectiveness, based on direct costs (initial cost minus maintenance savings) of gaseous fuel conversion systems, is comparable to that of the oxidation catalyst retrofit system. The total cost effectiveness of the gaseous fuel system becomes more favorable only when the unit cost of the gaseous fuel is much below that of gasoline. At the present time, this seems to be the case only for CNG, and that system has the disadvantage of a significantly reduced range (one-third that for gasoline). The high initial costs of the gaseous fuel conversion hardware would make implementation of that control strategy difficult, even if the gaseous fuel cost and supply situation were favorable.

## Table 1-8. Summary of Cost Effectiveness Information for Gaseous Fuel Conversion (Best Obtainable Values)

| Fuel | Initial Cost ($) | Maintenance Savings ($)[a] | Unit Fuel Price ($)[b] | Fuel Savings ($)[c] | Emissions gm/mi-1975 FTP | | | Cost Effectiveness[d] ($/lb) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Initial Costs and Maintenance Savings | | | Initial Costs and Maintenance and Fuel Savings | | |
| | | | | | HC | CO | NO$_x$ | HC | CO | NO$_x$ | HC | CO | NO$_x$ |
| Controlled Vehicles (1968-1971) (Baseline emissions: HC = 4.8, CO = 60, NO$_x$ = 4.8 gm/mi) | | | | | | | | | | | | | |
| LPG | 650 | 125 | 0.28/gal | -150 | 2.1 | 14.2 | 2.9 | 1.81 | 0.11 | 2.52 | 3.33 | 0.14 | 3.24 |
| CNG | 870 | 125 | 0.20/100 scf | 250 | 1.7 | 5.1 | 1.4 | 2.16 | 0.12 | 1.99 | 2.05 | 0.08 | 1.32 |
| LNG | 1020 | 125 | 0.28/gal | -300 | 1.7 | 5.1 | 1.4 | 2.6 | 0.15 | 2.39 | 3.95 | 0.22 | 2.61 |
| Controlled Vehicles (1972-1974) (Baseline emissions: HC = 2.8, CO = 30, NO$_x$ = 3 gm/mi) | | | | | | | | | | | | | |
| LPG | 650 | 125 | 0.28/gal | -150 | 1.5 | 2.7 | 1.1 | 3.18 | 0.18 | 2.52 | 4.08 | 0.23 | 3.24 |
| CNG | 870 | 125 | 0.20/100 scf | 250 | 1.0 | 2.0 | 0.7 | 3.77 | 0.24 | 2.95 | 2.50 | 0.16 | 1.95 |
| LNG | 1020 | 125 | 0.28/gal | -300 | 1.0 | 2.0 | 0.7 | 4.5 | 0.29 | 3.53 | 6.83 | 0.44 | 5.34 |

[a] Maintenance saving of 0.0025 $/mi for 50,000 miles.

[b] No Federal or State tax is included in the fuel costs.

[c] Fuel savings in 50,000 miles compared with operation with gasoline; negative sign means an increase in fuel costs.

[d] Lifetime of gaseous fuel conversion system is taken to be 50,000 miles.

### 1.2.4 Comparison of the Emission Reduction Potential and Cost Effectiveness of Various Hardware Type Emission Control Strategies for In-Use Vehicles

The emission reduction potential and cost effectiveness of the various control strategies for in-use vehicles have been discussed in the previous sections. For purposes of a direct comparison of these strategies, the results for light duty vehicles are summarized in Table 1-9. The emission reduction potential is expressed in terms of gm/mi per vehicle while the cost effectiveness is given as $/lb of pollutant eliminated. These cost effectiveness values (as well as all cost effectiveness values presented throughout this report) were determined by dividing the total per vehicle cost for a given emission control strategy by the corresponding values of per vehicle emission reduction for each emission specie (HC, CO, $NO_x$). Thus, they do not represent any attempt to prorate or apportion control costs among the three vehicle emissions considered. Results are given for HC and CO emissions and for controlled (1968-1971) and uncontrolled (pre-1968) vehicles. Data are not available to assess the impact of the various control strategies on vehicles of later model years. $NO_x$ emissions are not included in the summary table because their control was not an objective of the control strategies being compared. In general, the inclusion of an $NO_x$ control (EGR and/or vacuum delay) in a retrofit program will reduce its cost effectiveness (increase the $/lb value) for HC and CO reduction because of the associated fuel penalty. It is important to note that, for some strategies, the inclusion of the effect of incremental fuel costs significantly changes the cost effectiveness and in some cases could result in a net savings (NS) to the vehicle owner.

## Table 1-9. Comparison of the Emission Reduction Potential and Cost Effectiveness of In-Use Vehicle Control Strategies (Light Duty Vehicles)

| Control Strategy | Emission Reduction Potential and Cost Effectiveness [a] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Controlled Vehicles[b] (1968-1971) | | | | Uncontrolled Vehicles[b] (Pre-1968) | | | |
| | HC | | CO | | HC | | CO | |
| | Emission[c] Reduction | Cost[d] Effect. | Emission[c] Reduction | Cost[d] Effect. | Emission[c] Reduction | Cost[d] Effect. | Emission[c] Reduction | Cost[d] Effect. |
| I/M Approaches[e] | | | | | | | | |
| Loaded test (RR = 30%) | 0.62 | | 5.4 | | 1.16 | | 8.1 | |
| Excluding fuel savings | | 0.93 | | 0.106 | | 0.56 | | 0.080 |
| Including fuel savings[f] | | 0.63 | | 0.071 | | 0.30 | | 0.043 |
| Idle test (RR = 30%) | 0.475 | | 4.8 | | 0.89 | | 7.2 | |
| Excluding fuel savings | | 1.12 | | 0.111 | | 0.68 | | 0.084 |
| Including fuel savings | | 0.79 | | 0.078 | | 0.39 | | 0.049 |
| Retrofit Approaches[g] | | | | | | | | |
| Lean carburetion | 0.72 | | 30.0 | | 1.78 | | 54.0 | |
| Excluding fuel savings | | 0.57 | | 0.01 | | 0.23 | | 0.007 |
| Including fuel savings | | NS[h] | | NS | | NS | | NS |
| Lean carburetion + vacuum delay | 0.96 | | 30.0 | | 2.23 | | 49.5 | |
| Excluding fuel savings | | 0.47 | | 0.010 | | 0.20 | | 0.009 |
| Including fuel savings | | 0.47 | | 0.010 | | 0.20 | | 0.009 |
| Oxidation catalyst w/air pump | 3.36 | | 39.0 | | -- | | -- | |
| Excluding fuel savings | | 0.62 | | 0.05 | | -- | | -- |
| Including fuel savings | | 0.62 | | 0.05 | | -- | | -- |
| Gaseous fuel conversion | | | | | | | | |
| LPG (including fuel) | 2.70 | 3.33 | 45.0 | 0.14 | -- | | -- | |
| CNG | 3.10 | | 54.0 | | -- | | -- | |
| Excluding fuel savings | | 2.16 | | 0.12 | | | | |
| Including fuel savings | | 2.05 | | 0.08 | | | | |

[a] The cost effectiveness values for controlled and uncontrolled vehicles must be appropriately weighted to reflect their representative contributions to the total annual mileage of the composite vehicle population

[b] Baseline emissions: controlled vehicles - HC = 4.75 gm/mi
CO = 60 gm/mi; uncontrolled vehicles - HC = 8.90 gm/mi,
CO = 90 gm/mi; all emissions relative to the 1975 CVS-CH FTP.

[c] Emission reduction in gm/mi

[d] Cost effectiveness in $/lb of pollutant reduced

[e] The I/M portion of this table is based on a linear deterioration factor while no such factor has been applied to the retrofit portion

[f] Incremental fuel costs included; unit cost of gasoline - $0.50/gal

[g] The costs and emission reductions attributed to the retrofit strategies are incremental to the cost and effectiveness of an I/M strategy

[h] NS - Net savings

The emission reduction comparisons in Table 1-9 should be considered as representative class examples only, as there can be a wide variation of values within each control strategy class shown. For example, the I/M approach values shown are typical for a rejection rate of 30 percent only; higher or lower program rejection rates would result in different emission reduction values. Similarly, the cost effectiveness values in the table are necessarily restricted to the assumptions made with regard to control effectiveness, initial hardware costs, etc. However, they do provide an overview as to the relative comparative levels of cost effectiveness that the various in-use control strategies provide.

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1-5 An Analysis of the Economic Impact of Motor Vehicle Use Restrictions in Relation to Federal Ambient Air Quality Standards, Alan M. Voorhees and Association, Inc. (September 1973).

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1-7 "Appendix N - Emissions Reductions Achievable Through Inspection, Maintenance, and Retrofit of Light Duty Vehicles," Federal Register, Vol. 38, No. 110 (Friday, June 8, 1973).

# 2. EMISSION INSPECTION AND MAINTENANCE APPROACHES

## 2.1 INTRODUCTION

The increase of automotive emissions resulting from improper, inadequate, or insufficiently frequent maintenance affords the possibility of achieving significant reductions of motor vehicle emissions through the periodic inspection and/or enforced maintenance of in-use vehicles. This section summarizes currently available information concerning the alternative test procedures examined to date for the periodic inspection of extensive vehicle populations, the potential effectiveness of emission-related maintenance procedures for reducing automotive emission levels, and the costs and cost effectiveness values attributable to alternative inspection/maintenance (I/M) strategies.

### 2.1.1 Types of I/M Approaches

The general term "inspection/maintenance approaches" includes all procedures and strategies intended to improve the maintenance of in-use vehicles for the purpose of reducing their emissions. Some of the I/M approaches considered in detail in this section have separate inspection and maintenance phases, while others have only a maintenance phase. The various alternative I/M approaches can be divided into the following general categories:

a. Emission Inspection/Repair Approaches. Vehicles included in the program are subjected to an emission test and the results are compared with a set of predetermined failure criteria. Vehicles with emissions in excess of the inspection standards are rejected (failed) and are required to have maintenance performed to reduce the emission to acceptable levels. An emissions retest may be required after the maintenance to ensure that the failed vehicles have been brought into compliance with the emission inspection standards. The emission testing phase of this approach could be done in a system of inspection lanes provided by an appropriate State or municipal agency or in private garages that are certified, licensed, and supervised by an appropriate governmental agency. A third possibility is that random inspections could be performed by specially trained officers at mobile sites on highways and streets.

b. Engine Parameter Inspection/Repair Approaches. Each vehicle included in the program is subjected to a sequence of diagnostic tests to evaluate the operating condition of various emission-related systems and to determine if malfunctions or maladjustments are present. Vehicles showing measurements outside of accepted tolerance ranges are considered to have failed and are required to have corrective maintenance performed. This approach bypasses the measurement of each vehicle's emission levels, although in some cases emission measurements may be made to evaluate the state of certain vehicle systems (e.g., measurement of the idle CO concentration to evaluate the idle air/fuel ratio). The same possibilities of State lanes, private garages, and mobile sites exist for the inspection phase in this category as in the previous one.

c. Mandatory Maintenance Approaches. Each vehicle, independent of its emission levels or mechanical condition, is required to have specific maintenance performed at stated intervals. Thus, the inspection phase is eliminated and appropriate maintenance is specified for each type of vehicle. This maintenance program is identical for all vehicles of that type rather than being whatever maintenance is necessary to achieve compliance with an emission standard or to ensure that specific vehicle systems pass parameter checks.

In all cases, it is anticipated that private service garages and dealerships comprising the automotive repair industry would provide the requisite maintenance.

### 2.1.2 Criteria for the Evaluation of I/M Approaches

The following factors and criteria are important in assessing the feasibility, emission reduction potential, and cost effectiveness of the various I/M strategies.

a. The extent to which inadequate or improper maintenance by the general public causes in-use vehicles to differ from the original manufacturer's specifications.

b. The magnitude of the emission increases, which is the result of such deviations from manufacturer's specifications.

c. The effectiveness with which the inspection testing procedure can identify from among the entire vehicle population those vehicles with excessive emissions resulting from malfunctions and maladjustments of the engine and emission control system.

d. The diagnostic value of the inspection test results in identifying the specific maintenance actions required to restore the vehicle to a condition that is in compliance with the inspection standards.

e. The effectiveness of the repair industry in applying proper repair/maintenance procedures to reduce emissions from those vehicles identified as having malfunctions or maladjustments.

f. The average emission reductions that can be achieved for the serviced vehicles and the total vehicle population.

g. The fraction of the vehicles that must be tested and failed to achieve a desired emission reduction.

h. The rate and extent of the deterioration of vehicle emissions following maintenance/repair.

i. The relationship between the inspection test procedure used and the Federal Certification Test Procedure as it relates to the impact of vehicular emissions upon ambient air quality.

j. The initial capital investment required and the annual operating costs of the inspection facilities and program administration.

k. The maintenance (or repair) costs and indirect savings, such as improvements in fuel economy and vehicle driveability and reliability, due to the substitution of required maintenance for existing voluntary maintenance practices.

l. The ease with which the program can be implemented.

m. The citizen acceptance of the program.

n. The extent to which the I/M approach is applicable to vehicles with advanced control systems and/or alternative engines.

Some of the foregoing factors have been evaluated quantitatively for various alternative I/M approaches in the recent studies summarized in Table 2-1. As a result of these studies, a considerable body of information and data is available concerning various I/M approaches;

Table 2-1. Summary of Major Features of I/M Studies Conducted to Date

| I/M Strategy | Emissions Inspection Test | Maintenance Approach | Types of Vehicles in Fleet | Contractor/ Sponsor | Year of Study | Ref. |
|---|---|---|---|---|---|---|
| Emission inspection/ repair | Idle<br>Key Mode | Repair of failed vehicles | Precontrolled<br>Controlled<br>$NO_x$ controlled (Calif. 1971) | Olson/EPA | 1971-72 | 2-1 |
| Mandatory periodic maintenance | None | Specified maintenance procedures for all vehicles | Same as above | Clean Air Research Company/California Air Resources Board | 1972 | 2-3 |
| Emission inspection/ repair and mandatory periodic maintenance | Idle<br>Key Mode<br>Engine parameter | Repair of failed vehicles and specified maintenance procedure | Same as above | Northrop/California Air Resources Board | 1970 | 2-2 |
| Emission inspection/ repair and mandatory periodic maintenance | Engine parameters including emissions | Specified maintenance procedures | Same as above | TRW/EPA/CRC | 1968-73 | 2-4 |
| Emission inspection/ repair | Idle<br>Key Mode | Repair of failed vehicles | Precontrolled<br>Controlled | State of New Jersey with Clayton Manufacturing Co. | 1968-70 | 2-5, 2-6 |
| Emission measurements only | Key Mode | None | Same as above | Washington, D.C. | 1971-72 | 2-7 |
| Emission inspection/ repair | Idle/random highway | Repair of failed vehicles | Controlled (1966-1972, Calif.) | Scott Lab./ California Air Resources Board | 1973 | 2-8 |

however, it is limited and incomplete with respect to its usefulness in projecting the costs and benefits of I/M in the years ahead. In all the I/M studies cited, the comparisons of the various approaches examined were made on the basis of statistically equivalent fleets of precontrolled and controlled vehicles. In all cases, the vehicles used were 1971 or earlier models that had experienced no previous mandatory I/M program. Hence, the detailed comparisons found in Ref. 2-1 through 2-5 can only offer guidance as to what would result when the same approaches are applied to later model vehicles (1973, 1974, 1975, and beyond) with more advanced emission control systems. Thus, considerable engineering judgment is required to make quantitative estimates of the effectiveness of I/M on these later model vehicles.

In addition, the I/M process itself may significantly alter the emissions characteristics (i.e., the fraction of vehicles with emissions less than a given value) and state-of-repair of the current vehicle populations and, as a result, may change the relationships between failure criteria, failure rate (fraction failed), and the mean emission reduction achieved for a given failure rate and I/M approach. Hence, additional data similar to that reported in Ref. 2-1 through 2-5 will be required on a continuing basis to effectively plan I/M programs and to assess the evaluation criteria listed previously. Such continuing information and data will be required until I/M programs have been established for several years and the present rapid changes in new vehicle emission levels (standards) and emission control systems have stabilized.

## 2.2 EMISSION INSPECTION PROCEDURES

The inspection phase of an I/M program is a screening procedure applied to the population of in-use vehicles subject to I/M. Its function is to identify, for required maintenance, only those vehicles likely to exhibit significant emission reductions if given additional maintenance. The inspection procedure could also provide a check on the quality of the maintenance performed on the failed vehicles if they were required to be retested after maintenance. The inspection can be done either in an inspection lane or by a private garage.

Consideration of alternative test procedures that satisfy the requirements of the inspection process leads to the identification of two general categories: direct emission measurement tests and engine parameter tests. Detailed descriptions of several short emission test procedures (or cycles) that have been found useful for inspection purposes are given in the next section. The second category of inspection procedures, engine parameter tests, is discussed in Section 2.3.

### 2.2.1 Alternative Short Emission Test Procedures

The feasibility and effectiveness of the emission inspection/repair approach depends to an important extent upon the availability of emission test procedures that can rapidly and reliably identify vehicles whose emissions can be reduced through maintenance. Such emission test procedures are termed short emission test procedures (or cycles) to contrast them with the longer Federal Test Procedures (FTP) (1972 CVS-C or 1975 CVS-CH) that are used to obtain vehicle emissions for "new vehicle" certification purposes. Since the Federal Light Duty Vehicle Emissions Standards (gm/mi HC, CO, $NO_x$) are expressed relative to the Federal Test Procedure and vehicle contributions to emissions inventory and air quality calculations are based on the same driving cycle, the relationships between concentration and mass emissions obtained using the short emission test procedures and the longer FTP are of considerable importance. This subject and its effect on the acceptability of a given short test procedure for inspection purposes are discussed in Section 2.2.2.

The minimum requirements for an emissions test procedure to be acceptable for use on an emissions inspection lane are that it be quick (2 or 3 minutes at the most), applicable to vehicles in the condition in which they arrive at the inspection station (warmed-up), and capable of identifying a large percentage of the vehicles that would show high emissions if they were tested using the FTP. Additional characteristics, which are desirable but not absolutely necessary, are that the test procedure can be duplicated in most private garages to check the effectiveness of repairs,[*] yield meaningful diagnostic information to the mechanics for repair, and be well correlated to FTP emissions for the vehicle. Unfortunately, no short test procedure has yet been developed that completely meets all of these requirements. However, there are several that appear to be useful for emissions inspection even though they are not completely satisfactory in all respects. These short test procedures can be divided into three categories: [1] engine unloaded (idle), [2] engine loaded, steady state (simulated highway cruise), and [3] engine loaded, transient (simulated urban driving). The most highly developed tests in each category are the following:

Unloaded

Idle Test (idle rpm and 2500 rpm)

Loaded, Steady State

Key Mode (high cruise, low cruise, idle)

Loaded-Transient

New Jersey ACID[**] Cycle
New York City (NYC) Quick Cycle
EPA Short Test Cycle
Single cycle of seven-mode hot start test

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[*] In this case, the test procedure could be also used in the private garage to conduct the emission inspection.

[**] ACID-accelerate, cruise, idle, and decelerate.

Each of these test procedures is described in Table 2-2, together with related information concerning personnel, special test equipment, and instrumentation requirements and applications of the test procedure to date. In Table 2-3, the load and speed test conditions of the Key Mode cycle are further described. Speed and time characteristics of the various short test cycles are shown in Figure 2-1. Considerable data on the use of these test procedures are available from recent I/M studies in which they have been used.

Each of the short emissions tests has advantages and disadvantages relative to its use in an inspection lane test program. These advantages and disadvantages are listed in Tables 2-4 through 2-6.

### 2.2.2 Relatability and Discrimination Characteristics of Short Emission Test Procedures

Vehicle emissions (gm/mi) corresponding to the FTP (1972 CVS-C and 1975 CVS-CH) are used for evaluating the effect of the emissions of a particular vehicle or fleet of vehicles on air quality. Therefore, it is necessary to relate emissions taken using other test procedures to those emissions corresponding to the FTP. For purposes of evaluating I/M strategies, there are two different aspects of the relatability problem that are important. First, how the emissions of particular vehicles or fleets of vehicles using a test procedure other than the FTP correlate with those that would have been measured using the FTP. This is termed the "direct relatability of the two procedures." Second, how vehicles having high FTP emissions can be identified using a test procedure other than the FTP. This problem of setting pass-fail criteria for the short test procedures is termed the "discrimination problem." The discrimination process (identification of failed vehicles) must be applied on a vehicle-by-vehicle basis, while direct relatability can be applied either to single vehicles or a fleet of vehicles. These two aspects of the relatability problem (direct relatability and discrimination) are discussed briefly in the following sections.

## Table 2-2. Characteristics of Short Test Procedures for Emission Inspection

| Short Test | Cycle Description | Cycle Test Time[a] | Number of Technicians Required | Special Test Equipment Required | Instrumentation Required | Applications to Date |
|---|---|---|---|---|---|---|
| Idle | Idle in drive and/or freewheeling at 2500 rpm | Not applicable | 1 or 2 | None | HC and CO exhaust gas analyzers | N.J. test lane; Calif.-roadside; Calif.-end of assembly line |
| Key Mode | Steady-state at high cruise, low cruise, idle in drive (see Table 2-3 for load conditions). | 60 sec | 2 | Chassis dynamometer (single power absorption curve) | HC, CO, and $NO_x$ exhaust gas analyzers | Washington D.C. test lane; various I/M studies (EPA, N.J., NYC, Calif. ARB) |
| Shorter urban test cycles (New Jersey ACID cycle, NYC Quick Cycle) | Consist of accelerations, cruise, decelerations, and idle in drive (see Figure 2-1) | 60 to 80 sec (see Figure 2-1) | 2 | Chassis dynamometer (variable inertia and power absorption with automatic test settings) | CVS sampling system[b] - HC, CO, and $NO_x$ gas analyzers with computerized data reduction | Under development |
| Longer urban test cycles (e.g., EPA short test cycle and single cycle of the seven-mode hot start) | Seven to nine modes including combinations of acceleration, cruise, deceleration, and idle (see Figure 2-1 for mode diagrams) | 124 to 137 sec (see Figure 2-1) | 2 | Same as above | Same as above | End-of-assembly line testing by EPA and Calif. ARB; I/M studies by EPA contractors |

[a] This time includes only that required to operate the vehicle through the cycle and does not include set-up time.

[b] Integration of concentration values over the cycle is possible, but CVS sampling is preferable.

Table 2-3. Load and Speed Conditions for the Key Mode Test (Ref. 2-5)

| Vehicle Weight Class (lb) | Low Cruise Mode | | High Cruise Mode | |
|---|---|---|---|---|
| | Speed (mph) | Load (hp) | Speed (mph) | Load (hp) |
| Less than 2800 | 23 | 5 | 37 | 14 |
| 2800-3800 | 30 | 9 | 45 | 23 |
| Greater than 3800 | 33 | 11 | 49 | 29 |

Table 2-4. Advantages and Disadvantages of the Unloaded Idle Test Procedure

| Unloaded Idle Test | Advantages | Disadvantages |
|---|---|---|
| Idle rpm and 2500 rpm | 1. No dynamometer is required.<br>2. Can be duplicated at repair garages.<br>3. Owner can remain in vehicle during test.<br>4. Can be added to existing safety inspection lanes.<br>5. Can be duplicated for roadside random inspection. | 1. Emissions under loaded conditions are not measured.<br>2. Provides minimum direct diagnostic information to repair garages.<br>3. Poor correlation between idle and FTP CVS emissions.<br>4. Not applicable for $NO_x$ emission inspection. |

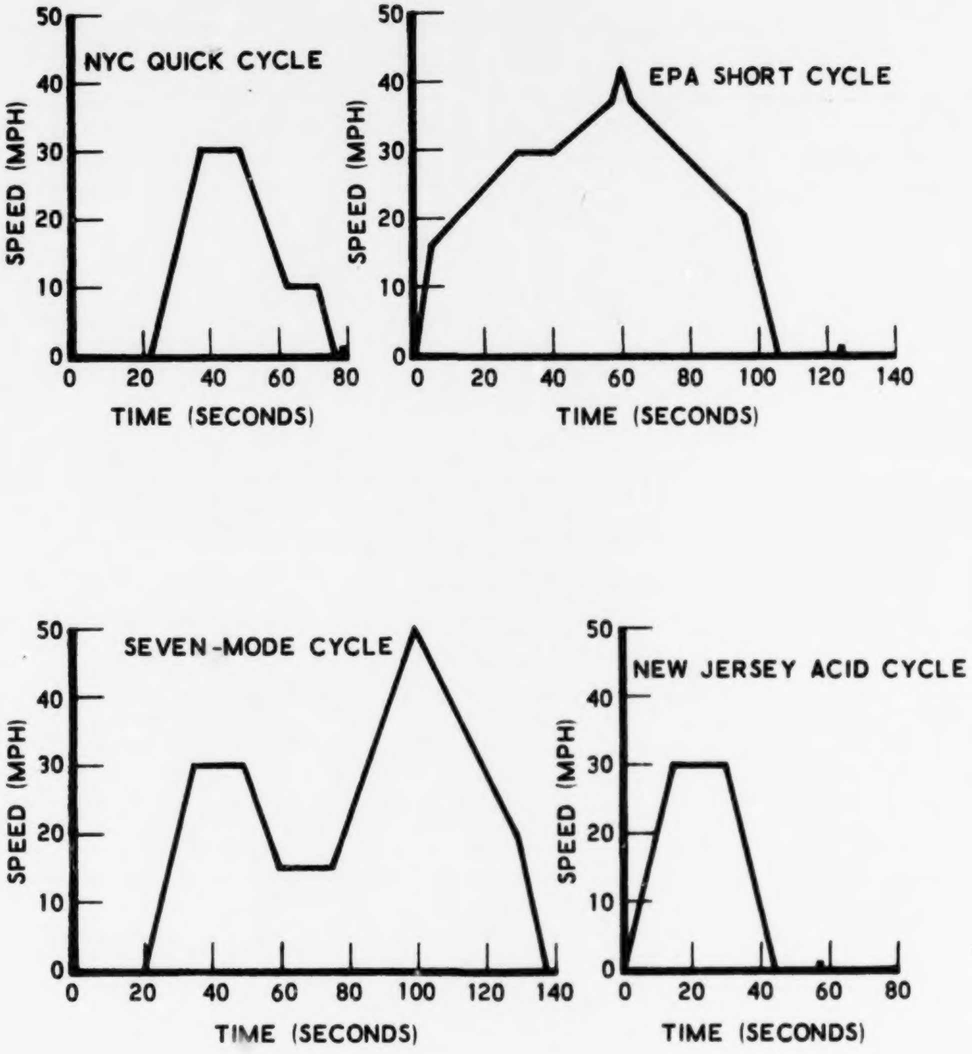

Figure 2-1. Speed and Time Characteristics of Short Urban Cycles

Table 2-5. Advantages and Disadvantages of Key Mode Test Procedure

| Loaded Key Mode Test | Advantages | Disadvantages |
|---|---|---|
| High cruise,<br>low cruise,<br>idle | 1. Engine loaded during test so emissions at load and high airflow conditions are measured. | 1. Power absorption dynamometer (single absorption curve) required. |
| | 2. Provides good diagnostic information to repair garages over the complete range of engine operating conditions. | 2. Test cannot be duplicated in most repair garages due to the need for a dynamometer. |
| | 3. Test cycle easily repeatable; no transients to follow. | 3. Owner probably cannot drive car during the test. |
| | 4. Applicable for $NO_x$ inspection.<br>5. May be applicable to catalyst equipped cars. | 4. Uncertain relationship between Key Mode and FTP CVS emissions for individual vehicles; however, the relationships of average fleet emissions are more likely to be acceptable for program evaluation, emission inventory, and air quality calculations. |

Table 2-6. Advantages and Disadvantages of Various Loaded Short Urban Test Cycles

| Short Urban Test Cycles | Advantages | Disadvantages |
|---|---|---|
| New Jersey ACID Cycle<br>New York City Quick Cycle<br>EPA Short Test Cycle<br>Single cycle of seven-mode hot start test | 1. Emission measured from both loaded cruise and transient engine modes. | 1. Computer needed for rapid on-line data reduction, especially if modal diagnostic information is desired. High initial cost. |
| | 2. Expected to provide closest correlation with FTP CVS emissions. | 2. Variable inertial and power absorption dynamometer needed. |
| | 3. Most direct evaluation of I/M program as related to emissions inventory. | 3. Owner cannot drive the vehicle during test. |
| | 4. Provides some diagnostic information to repair garages; possible to use on-line computer data reduction. | 4. Driving cycle difficult to follow accurately even by experienced technician; no possibility of averaging repeated cycles in short test. |
| | 5. May be applicable to $NO_x$ control and catalyst equipped vehicles. | 5. Test cannot be duplicated in most repair garages. |

### 2.2.2.1 Direct Relatability Between Short Test Procedures and the FTP

The emissions (gm/mi or exhaust gas concentrations) obtained from a particular vehicle using only the short test procedures are different than those obtained using the FTP because the preconditioning of the vehicle (hot start compared with cold start) and the test cycles (time history of engine loadings) are different. Despite this difference in emissions for particular vehicles, it is still possible that there is a useful relationship between the emissions from a short test procedure and the FTP when the mean (average) emissions of fleets of vehicles are considered. In this case, the criteria of acceptability of the correlation between the test procedures is the uncertainty in the inferred means of the FTP emissions of the fleet as predicted by the short test procedure. This approach seems to be useful for reasonable size fleets. The relatability of means is useful in evaluating I/M programs because (1) it makes it possible to relate surveillance data (taken using test procedures other than the FTP) to equivalent FTP emissions and to compare them with pertinent Federal Emission Standards, and (2) it permits the use of emission reduction/repair data taken using other test procedures such as the seven-mode hot start. In both cases, however, caution must be exercised in interpreting the results of such extrapolations. Since most short test results exhibit a wide degree of scatter and the relationships between these results and those from FTP tests are quite uncertain, this type of analysis can easily lead to false or distorted conclusions.

### 2.2.2.2 Discrimination Capability of Short Test

The primary objective of the inspection phase of an I/M program is to identify the vehicles that have high emissions that can be significantly reduced by proper maintenance. Ideally, pass-fail criteria would be determined for the short test procedure that would identify perfectly (without either errors of commission or omission)* those vehicles with emissions of one or more of the pollutants (HC, CO, $NO_x$) above standards set relative to the FTP. The pass-fail standards for a given model year vehicle would be related to the Federal Emission Standards for that model year.

Various approaches to discrimination (i.e., the identification of high emitters) using the short test procedures include (1) direct relatability, (2) optimization of discrimination errors, and (3) the engine diagnostic method. The objective of each approach is to select, for a fixed rejection rate, the greatest possible number of high emitters. In the I/M studies conducted to date, a combination of the direct relatability and engine diagnostic approaches have been found to be the most practical and effective. The emissions data needed to set pass-fail criteria by any other method is usually not available prior to the start of an I/M program or study.

The fraction of the emission reduction potential that is actually achieved in an I/M program depends to a large extent on the ability of the auto repair industry to properly isolate and repair the causes of the high emissions in the rejected vehicles. This interaction between the inspection and maintenance phases of the program has made it difficult to evaluate quantitatively the relative discrimination capabilities of the idle and loaded short test procedures based on the results of the I/M studies reported in Refs. 2-1 and 2-2.

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*An error of commission is an error in which the conclusion drawn from the short cycle test is that the vehicle is a high emitter and requires repair but where in fact it does not require repair as it would have passed the appropriate certification test. An error of omission is an error in which the vehicle is judged to be a low emitter by use of the short cycle test, when in fact it would have been shown to be a high emitter (above the standards) had it been tested by the appropriate certification test.

## 2.3 ALTERNATIVE MAINTENANCE PROCEDURES

The repair and/or adjustment of the engine or the emission control systems are the only operations that directly reduce emissions from in-use vehicles. Even if the inspection phase properly identifies the vehicles having high emissions, the mechanics must be able to locate and repair the malfunctions or maladjustments of the engine and/or control system that have led to the high emissions. Otherwise the primary objective of any I/M program — that of reducing emissions from in-use vehicles — cannot be achieved. Tests that can be used by mechanics to locate malfunctions/or maladjustments and/or to assess their impact on emissions are termed "engine-control system diagnostics tests." The auto repair industry must be knowledgeable of and efficient in the use of diagnostic tests and associated repair procedures for an I/M strategy to be cost effective. The differences between the various alternative I/M strategies as they concern the maintenance phase of the program are (1) at what stage in the I/M sequence, and (2) to what extent diagnostic tests are performed. These differences are noted in Table 2-7 where the major I/M strategies — emission inspection/repair, engine parameter inspection/repair, and mandatory periodic maintenance — are outlined, with emphasis on a description of the maintenance phase. The effectiveness (emission reduction and cost) of each of these I/M strategies is discussed in Sections 2.4 and 2.6. First, it is advantageous to consider the diagnostic tests and maintenance/repair procedures and how they relate to emission reductions. This is discussed in Section 2.3.1. In addition, emission test results obtained in the inspection phase using short test procedures can be used to select which of the diagnostics tests are the most appropriate as further aids in making cost-effective repairs. This topic is discussed in Section 2.3.2.

Table 2-7. Maintenance Approaches in Various I/M Strategies

| I/M Strategy | Maintenance Approach | Emission[a] Inspection | Engine Parameter Inspection | Vehicles[b] Serviced | Extent of Diagnostic Tests and Service |
|---|---|---|---|---|---|
| Emission Inspection/ Repair | Repair of failed vehicles to pass an emissions retest | All vehicles using a short test procedure | None | Vehicles that fail emissions inspection | Only tests needed to make repairs so that the vehicle passes the emissions retest |
| Engine Parameter Inspection/Repair | Repair of failed vehicles to pass an engine parameter retest | None | All vehicles using a specified procedure | Vehicles that fail engine parameter inspection | Tests required to correct difficiencies found by the diagnostic-type inspection |
| Mandatory Periodic Maintenance | Specified periodic maintenance[c] | None | None | All vehicles | Tests and service required to perform specified maintenance |

[a] Inspection performed in State-operated or franchised lanes, or in private garages.

[b] Service performed in private garages.

[c] Maintenance specified in detail by the State.

### 2.3.1 Engine and Emission Control System Diagnostic and Parameter Tests and the Sensitivity of Emissions to Particular Malfunctions

The EPA Certification Procedures for vehicles of each model year are intended to insure that if the engine is kept reasonably well-tuned and the emissions control systems are maintained according to manufacturer's instructions most in-use vehicles will have exhaust emissions less than the appropriate Federal Standards for that model year for up to 50,000 miles. If, however, malfunctions or maladjustments are present in either the engine or emission control systems of the vehicle, the emissions can be above the standards for the vehicle within the first few thousand miles of use. There have been several in-depth studies (Refs. 2-3 and 2-4) of the effect of engine and control system malfunctions on emissions for vehicles currently on the road and a projection of such effects for 1975-77 vehicles having more advanced emission control systems (Ref. 2-9). In this section of the report, the information and data reported in Refs. 2-1 through 2-4, 2-9, and 2-10 are reviewed and consolidated with emphasis on the following aspects of the emissions/maintenance problem:

a. Diagnostic and parameter test procedures and required equipment/instruments

b. Sensitivity of emissions to particular malfunctions or maladjustments

c. Frequency of occurrence of common malfunctions in current and future vehicle populations

#### 2.3.1.1 Diagnostic and Parameter Test Procedures and Required Equipment

There are many components and systems that must be checked to determine the state-of-operation or the need-for-repair of the engine and emission control systems on a vehicle. These components and systems can be categorized as follows:

a. Engine

1. Idle System (rpm, air/fuel ratio)
2. Major Engine Components
   - Intake and exhaust values
   - Cylinder rings (compression)
3. Induction/Fuel System
   - Carburetor (idle and main systems)
   - Fuel pump
   - Air filter
   - Fuel system filter
4. Warm-Up System
   - Choke
   - Heat riser valve
   - Carburetor air preheater
5. Ignition System
   - Basic timing
   - Primary ignition circuit
   - Secondary ignition circuit
   - Vacuum spark advance

b. Emission Control Systems

1. Positive Crankcase Ventilation System
   - PCV valve
2. $NO_x$ Control System
   - Spark advance control
   - Exhaust gas recirculation (EGR) valve
3. Air Injection System
   - Air pump
   - Check and anti-backfire valves
4. Oxidation Catalyst System
   - Catalyst activity
   - Container integrity

Diagnostic and parameter tests and the equipment and instruments needed to perform them are available for checking all the components and systems listed above. These tests involve the functional check of components, measurement of engine parameters at idle and under load, and measurement of vehicle emissions in various steady-state operating modes. A summary of the diagnostic tests and the equipment needed are given in Table 2-8. Also indicated in the table are an estimate of the time required and the cost of the equipment and instruments for each test. It is clear from Table 2-8 that the accumulated time (labor) that would be required to perform all the tests is sufficiently long that it is unlikely such a complete diagnostic/parameter test procedure would be practical for all vehicles at an engine parameter inspection or during every periodic maintenance. Hence, it is of importance to know how sensitive the emissions are to particular malfunctions and maladjustments in various systems and what the frequency of occurrence of the various malfunctions can be expected to be in vehicle populations having only voluntary maintenance.

### 2.3.1.2 Sensitivity of Emissions to Particular Malfunctions

Qualitative estimates of the effect of particular engine and control system malfunctions and maladjustments in HC, CO, $NO_x$ emissions are given in Table 2-9. Information is included for vehicles with advanced control systems such as EGR and catalytic converters. The sensitivity rankings noted in Table 2-9 are given in terms of H (high), M (medium), and L (low).

Many of the components that can have a large effect on emissions have a manufacturer suggested service interval of 6 months to one year (12,000 miles) even though the mean time to failure is much longer. Service and/or replacement of the many components and systems of the increasingly complex engine and emission control systems can be expensive if done at the manufacturer's suggested intervals. Hence, many vehicle owners do not have the service done as often as needed to maintain low emissions from the

## Table 2-8. Summary of Engine and Emission Control System Diagnostic Tests and Associated Equipment/Instruments

Engine Systems

| Component/System Tested | Engine Operating Mode | Type of Test | Time Required[a] (minutes) | Equipment Required | Cost of Equipment ($) |
|---|---|---|---|---|---|
| Idle System | | | | | |
| RPM | Idle | Engine parameter measurement | 1-2 | Engine analyzer | 100 - 200 |
| Air/fuel ratio | Idle | Engine parameter measurement | | Engine analyzer | 100 - 200 |
| Major Engine Components | | | | | |
| Exhaust valves | Idle/loaded | Emission measurement | 30-45 | HC/CO analyzer | 1000 - 1500 |
| Cylinder compression (rings) | Idle/loaded | Engine parameter measurement | | compression tester/cylinder leakage tester | 50 - 150 |
| Induction/Fuel System | | | | | |
| Carburetor | | | | | |
| Idle | Idle | Emission measurement | 2-5 | HC/CO analyzer | 1000 - 1500 |
| Main system | Loaded[b] | Emission measurement | | HC/CO analyzer | 1000 - 1500 |
| Air filter element | Off/loaded | Visual/engine parameter measurement | 1-2 | Air filter tester | 25 - 50 |
| Fuel filter | Off | Visual/mileage | 1-2 | None | |
| Warm-Up System | | | | | |
| Choke | Off | Visual/functional | 2-3 | None | |
| Heat riser valve | Off | Visual/functional | 2-3 | None | |
| Ignition System | | | | | |
| Basic timing | Idle | Engine parameter measurement | 1-2 | Engine analyzer | 100 - 200 |
| Primary ignition system | Idle/loaded | Engine parameter measurement | 2-5 | Engine analyzer[c] and ignition scope | 1500 - 2500 |
| Secondary ignition system | Idle/loaded | Engine parameter measurement | | | |
| Vacuum spark advance | Loaded | Engine parameter measurement | 1-2 | Distributor advance tester | 200 |

[a] After engine is warmed up and required equipment is available and calibrated.

[b] Tests at loaded engine modes require a simple (single-power absorption curve) dynamometer (cost: approximately $3500).

[c] Advanced engine analyzers (costing $4000-$6000) are being marketed that offer complete engine diagnostics capability and exhaust gas analysis in one unit, but less expensive engine analyzers/ignition scope units are suitable for testing ignition systems.

## Table 2-8. Summary of Engine and Emission Control System Diagnostic Tests and Associated Equipment/Instruments (continued)

Emission Control Systems

| Component/System Tested | Engine Operating Mode | Type of Test | Time Required (minutes) | Equipment Required | Cost of Equipment ($) |
|---|---|---|---|---|---|
| Positive Crankcase Ventilation | | | | | |
| PCV | Idle/loaded | Engine parameter measurement | 1-2 | Crankcase pressure gauge and PCV flow meter | 50 |
| $NO_x$ Control System | | | | | |
| Spark advance control | Loaded | Functional/engine parameter measurement | 1-2 | Advanced engine[d] analyzer or distributor advance tester | 4000 - 6000<br>200 |
| Exhaust gas recirculation EGR valve | Off/loaded | Functional/emissions measurement | 1-2 | $NO_x$ analyzer[e] | 1500 - 3000 |
| Air Injection System | | | | | |
| Air pump | Idle/2500 rpm | Engine parameter | 2-5 | Pressure gauge | 10 |
| Check and anti-backfire valves | Idle/2500 rmp | Functional | | None | |
| Oxidization Catalyst System | | | | | |
| Catalyst activity | Idle/loaded | Emission measurement | 2-5 | HC/CO analyzer | 1000 - 1500 |
| Container integrity | Off/idle | Visual | | None | |

[d] The advanced engine analyzer units can be used to check spark advance control system with the vehicle on a dynamometer. There are also functional check procedures available.

[e] This $NO_x$ analyzer is the NDIR type. Present price is about $3000/unit, but with increased market, price should be comparable to HC/CO analyzers.

Table 2-9. Effect on Emissions of Various Engine/Emission Control System Component Malfunctions/Maladjustments (Ref. 2-9)

| Component | HC | CO | $NO_x$ |
|---|---|---|---|
| Engine Components | | | |
| Idle System | | | |
| Idle mixture | M | H | L |
| Idle rpm | M | M | |
| Exhaust Valve Leak | H | M | |
| Compression (low) | M | H | |
| Induction/Fuel System | | | |
| Carburetor | M | H | L |
| Metering rods | M | H | L |
| Internal vents | L | M | L |
| Float | M | M | L |
| Power jet | M | H | |
| Accelerating pump | L | L | |
| Air filter element | L | M | |
| Fuel pump | L | L | L |
| Fuel filter | L | L | |
| Intake manifold leak | M | L | |
| Warm-Up System | | | |
| Choke | H | H | L |
| Heat riser valve | M | M | |
| Air cleaner thermostat | M | M | L |
| Ignition System | | | |
| Basic timing | L | M | M |
| Spark plugs | H | | M |
| Plug wires | H | | M |
| Coil | H | | |
| Distributor, condenser | M | | |
| Points | H | | |
| Electronic ignition | H | L | M |
| Transmission controlled spark | | | M |
| Vacuum delay valve | M | | M |
| Centrifugal advance | M | | M |
| Emission Control System Components | | | |
| PCV System | | | |
| PCV valve | M | H | |
| $NO_x$ Control System | | | |
| Spark advance control | M | | H |
| EGR valve | | | H |
| Reduction catalyst | | | H |
| Air Injection System | | | |
| Air pump | H | H | |
| Air pump belt (slip) | M | M | |
| Check valve | H | H | |
| Anti-backfire valve | M | M | |
| Oxidation Catalyst | | | |
| Catalyst activity | H | H | |
| Container integrity | H | H | |

vehicles. Repairs are made in most cases when the owner notices a degradation in vehicle reliability, driveability, performance, or fuel economy. Unfortunately, the same changes that cause a deterioration of emissions with mileage may also lead to improvements in some of these areas of importance to the vehicle owner. Hence, many conditions leading to moderate or even large increases in emissions are not likely to lead the owner to voluntarily have the vehicle serviced. The extent of the engine and control system malfunctions or maladjustments that are tolerable from an emissions point of view is considerably smaller than that tolerable to many vehicle owners from the viewpoint of reliability, performance, etc. This becomes particularly true in the case of older vehicles that tend to be driven with the minimum of maintenance as long as they are reasonably reliable. Fortunately, the average emissions from the population of older vehicles tend to stabilize as unavoidable repairs (e.g., ignition wiring, rebuilt carburetors, valve and ring replacement, etc.) are made, which results in large reductions in emissions from the repaired vehicles. Surveillance data indicates, however, that the stabilized emission levels are well above the emission potential for those model years.

The qualitative effects of various engine and emission control system malfunctions on emissions (HC, CO, $NO_x$) have been given in Table 2-9. In a number of cases, it is also possible to estimate quantitatively these same effects. The primary sources of this type of data are Refs. 2-4 and 2-9. The quantitative effects can be expressed in terms of the incremental changes in the emission of a particular pollutant (e.g., $\Delta$ gm/mi CO) for a specified failure or maladjustment (e.g., an inoperative spark advance on-off switch or delay valve; degrees advance from specification in basic timing). In summarizing the emission changes due to malfunctions, it is convenient to consider three categories: (1) minor engine or control system maladjustments or failures, (2) major engine problems, (3) major emission control system malfunctions.

The effects of various minor engine maladjustments on emissions are summarized in Table 2-10 for precontrolled (pre-1968), controlled

Table 2-10. The Quantitative Effect of Minor Engine/Emission Control System Malfunctions/Maladjustments on Emissions (Ref. 2-4)

| Item | Change in Emissions | | |
|---|---|---|---|
| Basic Timing | Δgm/mi[d] per degree advance | | |
| Vehicle Type | HC | CO | $NO_x$ |
| Precontrolled[a] | 0.06 | -0.95 | 0.14 |
| Controlled[b] | 0.05 | -0.34 | 0.095 |
| $NO_x$ Control[c] | 0.085 | -1.03 | 0.15 |
| Idle RPM | Δgm/mi per 100 rpm increase | | |
| Vehicle Type | HC | CO | $NO_x$ |
| Precontrolled | -0.29 | 2.8 | 0.02 |
| Controlled | -0.55 | 2.1 | 0.03 |
| $NO_x$ Control | -0.06 | 2.2 | 0.05 |
| PCV Valve | Δgm/mi per cfm[e] restriction | | |
| Vehicle Type | HC | CO | $NO_x$ |
| Precontrolled | -0.06 | 5.5 | -0.12 |
| Controlled | 0.20 | 6.0 | -0.20 |
| $NO_x$ Control | 0.28 | 15.9 | -0.38 |
| Air Cleaner | Δgm/mi per 12-1/2% area blockage | | |
| Vehicle Type | HC | CO | $NO_x$ |
| Precontrolled | 0.025 | 5.0 | -0.14 |
| Controlled | 0.040 | 3.4 | -0.09 |
| $NO_x$ Control | 0.040 | 2.3 | -0.12 |
| Idle CO | Δgm/mi per 1% increase in idle CO | | |
| Vehicle Type | HC | CO | $NO_x$ |
| Precontrolled | 0.36 | 4.2 | 0.21 |
| Controlled | 0.03 | 7.2 | 0.03 |
| $NO_x$ Control | 0.08 | 7.5 | -0.07 |

[a] Pre-1968

[b] 1968-1970

[c] California 1971

[d] All emissions measured using 1972 CVS-C; positive values indicate an increase in emissions, negative values indicate a decrease in emissions.

[e] Cubic feet per minute flow rate

(1968-1970), and $NO_x$ controlled (Calif. 1971) vehicles. The magnitude of the unit reference deviation was selected so that deviations measured in current in-use vehicle populations are a reasonable multiple of the reference unit. For the most part, taken singly, the effect of the minor engine maladjustments are reasonably small (1 to 2 gm/mi on HC and 5 to 10 gm/mi on CO), but the accumulated effect of several maladjustments occurring simultaneously can result in a vehicle having emissions far above an acceptable level for that model year. This category of malfunctions affects a significant fraction of the vehicles in the population, but the emission increase of many of the affected vehicles is relatively small.

As indicated in Table 2-11, the situation relative to emission increases due to major engine problems, such as ignition misfire and carburetor and exhaust valve problems, is much different. In this case, the magnitude of the emission increase due to a single problem is very large; however, the fraction of vehicles having these problems is relatively small. Proper identification in the inspection phase of these vehicles, especially those having main system carburetor problems, is particularly desirable.

The third category of emission-related malfunctions is concerned with the emission control system itself. In the case of $NO_x$ control, if the emission control system is integral with the engine system, its malfunction may in some instances cause a deterimental effect on engine operation or vehicle driveability or reliability. In the case of catalytic control of HC and CO emissions, a malfunction or deterioration of the oxidation catalyst or air pump has no effect on engine operation, since the exhaust gases are treated after they leave the engine. As indicated in Table 2-12, the magnitude of emission increases due to major malfunctions in the emission control systems are large (both in absolute and percentage terms). In the case of the catalyst, even a deterioration of 20 to 30 percent in catalytic activity results in significant increases in emissions. In many instances, minor engine maladjustments would be masked if catalytic activity is high; however, major engine problems can lead to rapid catalyst deterioration and a subsequent

Table 2-11. The Effect of Major Engine Malfunctions on Emissions (Ref. 2-4)

| Malfunction[a] | Change in Emissions (gm/mi)[b] | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| Ignition Misfire (% of time) | | | |
| 2 | 4 | | |
| 6 | 12 | | |
| 12 | 25 | | |
| Main System Carburetor Calibration | | 50-150 | |
| Leaking Exhaust Valves or Low Compression | 5-10 | | |

[a] All of these major engine problems result in reduced $NO_x$ emissions.

[b] Increase in emissions measured using the 1975 CVS-CH test procedure.

Table 2-12. The Effect of Major Emission Control System Failures on Emissions (Ref. 2-9)

| System Failure | Change in Vehicle Emissions[a] (gm/mi) | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| $NO_x$ Control System | | | |
| Spark advance (off-on) switch[b] failure | | | 1-1.5 |
| Spark advance delay valve[b] failure | | | 0.5-1.0 |
| EGR valve failure | | | 1.5-2.5 |
| Oxidation Catalyst System | | | |
| Air pump failure | 1 | 10 | |
| Catalyst[c] failure | | | |
| Total failure | 2-3 | 20-30 | |
| 30% decrease in catalytic activity | 0.5-1 | 5-10 | |
| 60% decrease in catalytic activity | 1.5-2 | 15-20 | |

[a] Increase in emissions measured using the 1975 CVS-CH test procedure.

[b] Component inoperative.

[c] Assuming normal engine operation; effect would be greater if other malfunctions are present.

very large increase in emissions. Hence, it is necessary to properly identify vehicles having major engine problems even when an oxidation catalyst is used for emission control.

### 2.3.1.3 Frequency of Occurrence of Various Malfunctions

It is also of interest to know how often the various malfunctions occur in typical vehicle populations and how large the deviations from manufacturer's specifications are for those components and systems that normally need adjustment. Such information, as shown in Tables 2-13 and 2-14, has been collected in various I/M programs by direct measurement of engine parameters and emissions (Ref. 2-4) or by extracting data from mechanics records (Refs. 2-3 and 2-10) of the kinds of repairs undertaken and the replacement parts used. As shown in the tables, a wide range in the state of repair of vehicles exists in current vehicle populations and careful diagnostic work by mechanics is required to locate the malfunctions present in a particular vehicle at a reasonable cost. In general, in order of frequency of occurrence, the various malfunctions rank as follows: idle adjustments, ignition problems (plugs, points, wiring), main system carburetor problems, and exhaust valves. Information on the occurrence of malfunctions of emission control components, such as $NO_x$ control (spark advance), air pump, etc., on newer model vehicles is quite sparse. Further, essentially no maintenance information is available on malfunctions of EGR valves and only limited durability test fleet data is available for oxidation catalysts.

### 2.3.2 Maintenance Phase Tune-Up/Repair Procedures

It was found in early I/M studies that unless the diagnostic and repair procedures were systematized and the mechanics were carefully instructed on their application and the relationships between emissions and various engine malfunctions and adjustments, resultant emission reductions from the program would be quite small and the cost of the tune-up and repair work would be quite high. Hence, in most of the I/M studies previously referenced (Refs. 2-1 through 2-4) the development of diagnostic, tune-up

Table 2-13. Emission and Engine Parameter Distributions for Two Vehicle Fleets[a] (Ref. 2-4)

| Location<br>Model Year<br>Parameters | Precontrolled Vehicles | | | | Controlled Vehicles | | | | $NO_x$-Controlled Vehicles | |
|---|---|---|---|---|---|---|---|---|---|---|
| | California[b] 1960-1965 | | Michigan[c] 1960-1967 | | California 1966-1970 | | Michigan 1968-1971 | | California 1971 | |
| | $\bar{X}$[d] | $\sigma$[e] | $\bar{X}$ | $\sigma$ | $\bar{X}$ | $\sigma$ | $\bar{X}$ | $\sigma$ | $\bar{X}$ | $\sigma$ |
| High cruise | | | | | | | | | | |
| HC, ppm | 383 | 450 | 332 | 374 | 222 | 306 | 198 | 107 | 135 | 56 |
| CO, volume % | 3.43 | 2.6 | 1.64 | 1.5 | 1.22 | 1.3 | 0.69 | 0.81 | 0.87 | 1.16 |
| NO, ppm | 1666 | 864 | - | - | 2613 | 976 | - | - | 2537 | 740 |
| Idle | | | | | | | | | | |
| HC, ppm | 865 | 989 | 603 | 582 | 376 | 546 | 300 | 230 | 240 | 199 |
| CO, volume % | 6.08 | 3.0 | 4.50 | 3.1 | 4.09 | 2.6 | 3.15 | 2.5 | 3.34 | 2.7 |
| NO, ppm | 126.8 | 122 | - | - | 124.2 | 82 | - | - | 168 | 96 |
| Timing, deg (deviation) | 0.35 | 5.7 | 0.62 | 6.0 | 0.50 | 4.6 | 1.07 | 3.7 | 0.17 | 3.4 |
| Idle speed, rpm (deviation) | 77.9 | 137 | 108.5 | 146 | -18.2 | 108 | 2.5 | 90 | -5.68 | 138 |
| Air cleaner restriction, deg | 60.0 | 53 | 61.7 | 45 | 45.6 | 53 | 47 | 44 | 28.8 | 43 |
| High cruise, PCV flow, $ft^3/min$ | 2.87 | 1.3 | 2.86 | 1.3 | 2.62 | 0.97 | 2.85 | 1.2 | 2.58 | 0.90 |
| Choke kick, in. (deviation) | 0.009 | 0.049 | -0.051 | 0.065 | -0.004 | 0.046 | -0.037 | 0.064 | -0.010 | 0.041 |
| Heat riser, % failed | 53.1 | - | 68.0 | - | 44.0 | - | 42.5 | - | 3.4 | - |
| Vacuum diaphragm, % failed | 25.0 | - | 32.6 | - | 21.7 | - | 21.3 | - | 0.0 | - |
| High cruise, misfire, % | 12.3 | 11.3 | 14.5 | 1.8 | 2.6 | 0.4 | 4.7 | 0.4 | - | - |
| Low cruise, misfire, % | 14.4 | 9.6 | 15.1 | 1.7 | 4.6 | 3.6 | 4.8 | 2.4 | - | - |
| Idle misfire, % | 17.5 | 12.0 | 13.9 | 3.8 | 11.5 | 9.7 | 4.2 | 0.9 | - | - |
| Air pump, % failed | - | - | - | - | 8.1 | - | - | - | - | - |
| $NO_x$ control, % failed | - | - | - | - | - | - | - | - | 4.9 | - |
| Mileage, miles | 83358 | 26047 | 58280 | 19377 | 43786 | 20567 | 27863 | 17340 | 8059 | 6451 |

[a] Vehicles in "as-received" or in-use condition, prior to any further maintenance or repair.

[b] Fleet of California vehicles

[c] Fleet of Michigan vehicles

[d] $\bar{X}$ - mean value of the parameter

[e] $\sigma$ - Standard deviation of parameter distribution

Table 2-14. Parts Replaced During Minimum Pollution Capability Tune-Ups[a] (Ref. 2-3)

| Part | % of Vehicles Receiving Parts[b] |
|---|---|
| Spark plugs | 56 |
| Air filters | 47 |
| Distributor points | 4 |
| Ignition wires | |
| Complete set | 5 |
| Individual wires | 7 |
| PCV valves | 10 |
| Carburetor jets | 4 |
| Carburetor rebuilt kit | 5 |
| Replacement carburetor | 3 |
| Distributor cap | 3 |
| Distributor rotor | 3 |
| Carburetor choke parts | 2 |

[a] Vehicles were tuned up to the extent necessary to minimize their exhaust emissions.

[b] All cars in fleet received a tune-up.

and repair procedures was an important part of the effort whether the study included a separate inspection phase (Refs. 2-1 and 2-2) to identify high emitters and only failed vehicles were serviced, or the entire fleet was subjected to a specified maintenance program (Refs. 2-3 and 2-4). Diagnostic and/or maintenance procedures have been developed from the following three points of view:

a. Maintenance after an idle inspection test
b. Maintenance after a loaded (Key Mode) inspection test
c. Mandatory maintenance and/or engine parameter inspection of all vehicles

The objective in each case is to achieve large average emission reduction at low average repair cost. A common approach, termed the "truth chart approach," has evolved in all three maintenance cases. It apparently was started by the Clayton Manufacturing Company in 1968 in connection with the Key Mode inspection test and has been adopted more recently for use with the idle test and even as the framework on which to plan a mandatory maintenance procedure. The application of the truth chart approach to each of the three maintenance approaches above is discussed in the following subsections.

### 2.3.2.1 Maintenance After an Idle Emissions Test

The basic assumption of the idle test is that high idle CO and HC emissions are a reliable indication of high emissions of these same pollutants on a FTP-CVS test. Therefore, in making repairs on vehicles that have failed the idle test, it is essential that it be possible to reliably diagnose malfunctions that result in high emissions in loaded modes, which are important in the FTP. Much of the effort in developing diagnostic and repair procedures and truth charts for use after the idle test has been directed toward this problem. In Ref. 2-10, this aspect of idle test maintenance is considered in detail. Since it is not possible to load the engine during maintenance without a dynamometer, the off-idle malfunctions must be inferred from engine parameter and emissions data taken with the engine in a free-wheeling condition. It was found (Ref. 2-10) that comparison of emissions at idle rpm with those at 2500 rpm (free wheeling) can in some cases yield information useful in diagnosing off-idle malfunctions. The most difficult engine malfunctions to recognize using idle test maintenance procedures are incipient ignition misfire and main system carburetor problems. Both of these malfunctions result in very large increases in emissions.

Typical idle test maintenance procedures and truth charts are extensive in detail and are not presented here in the interest of brevity. Effective application of these procedures requires instruction of mechanics in their use. At the present time, most mechanics are not accustomed to performing emission reduction-oriented tune-ups and repairs using emission measuring instrumentation (HC/CO gas analyzers) as a tool. There is considerable evidence that at least initially many errors are made by mechanics in making the needed repairs. The situation should improve as mechanics become more experienced in making emission-oriented repairs.

#### 2.3.2.2 Maintenance After a Loaded (Key Mode) Inspection Test

Diagnostic procedures and truth charts for use with loaded mode (Key Mode) emission inspection results have been developed by the Clayton Manufacturing Company. Classroom instructions on the use of the truth charts and dynamometer/vehicle demonstrations of the effect of various engine malfunctions on emissions have been given to mechanics by Clayton personnel as part of several I/M studies (Refs. 2-1, 2-2, and 2-5). Since emissions data are available to the mechanic from loaded as well as the idle engine operating modes, some engine malfunctions are indicated to the mechanic more pointedly and with less ambiguity than when only unloaded (idle and 2500 rpm) emissions data are available. This should result in fewer errors by mechanics in identifying the malfunctions causing high emissions. Almost all the field experience with the Key Mode system has been with HC and CO emissions on pre-1971 model vehicles, but $NO_x$ emission data from loaded (cruise) modes should permit its use for $NO_x$ inspection and repair also.

A typical Key Mode emission report card is shown in Figure 2-2. Note that maximum values for HC and CO are shown for each mode. These values, which would be different for vehicles with differing emission control potential, are well below the failure criteria for the vehicle of interest. They indicate emission levels for a normally functioning engine in that mode. A complete set of diagnostic truth charts has been developed for use by mechanics (Ref. 2-11). It is assumed that if a mechanic correctly diagnoses the reason for the high emissions from a vehicle, he will have a better chance of repairing it properly.

#### 2.3.2.3 Mandatory Maintenance and/or Engine Parameter Inspection of all Vehicles

A reasonable fraction of the vehicles in use are maintained reasonably well voluntarily by owners and it is commonly assumed that it is primarily the poorly maintained or neglected vehicles that are the high emitters. However, if each in-use vehicle was subjected to prescribed mandatory annual maintenance or engine parameter inspection/repair, the average emissions from in-use vehicles would be significantly reduced. This approach would be even more attractive if a functional check on components, such as the EGR valve, air pump, and oxidation catalyst,* in the more advanced emission control systems would be an effective way of insuring low emissions from late (and future) model vehicles.

There have been several I/M studies (especially in California) in which the mandatory maintenance approach has been evaluated. In this approach, the State would specify portions of the vehicle manufacturer's suggested maintenance procedure to be followed by private garages. Two such procedures are outlined in Refs. 2-2 and 2-3. These procedures would have to be extended to include functional checks of $NO_x$ control systems

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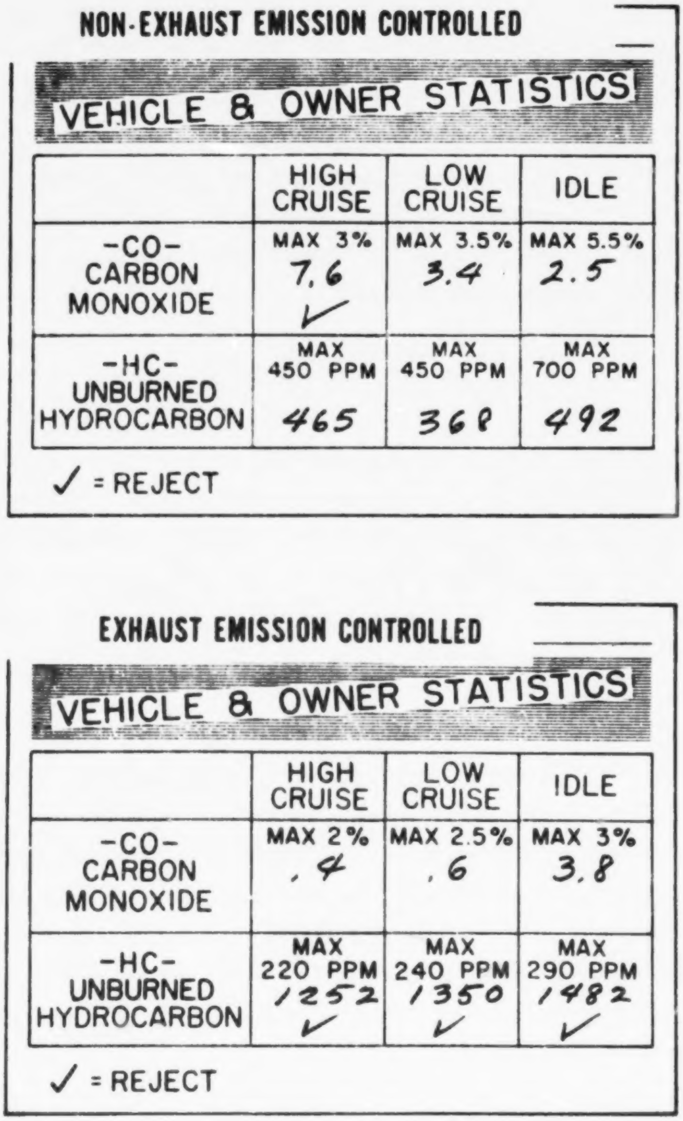
*A catalyst activity check, in which idle HC emissions with a purposely shorted spark plug are measured, has been suggested



**NON-EXHAUST EMISSION CONTROLLED**

VEHICLE & OWNER STATISTICS

| | HIGH CRUISE | LOW CRUISE | IDLE |
|---|---|---|---|
| -CO- CARBON MONOXIDE | MAX 3%<br>7.6<br>✓ | MAX 3.5%<br>3.4 | MAX 5.5%<br>2.5 |
| -HC- UNBURNED HYDROCARBON | MAX 450 PPM<br>465 | MAX 450 PPM<br>368 | MAX 700 PPM<br>492 |

✓ = REJECT

**EXHAUST EMISSION CONTROLLED**

VEHICLE & OWNER STATISTICS

| | HIGH CRUISE | LOW CRUISE | IDLE |
|---|---|---|---|
| -CO- CARBON MONOXIDE | MAX 2%<br>.4 | MAX 2.5%<br>.6 | MAX 3%<br>3.8 |
| -HC- UNBURNED HYDROCARBON | MAX 220 PPM<br>1252<br>✓ | MAX 240 PPM<br>1350<br>✓ | MAX 290 PPM<br>1482<br>✓ |

✓ = REJECT

Figure 2-2. Typical Key Mode Report Card (Ref. 2-11)

(spark advance on-off switch and/or EGR valve) and the activity of the oxidation catalyst if the procedures were to be applied to late (and future) model vehicles.

The prescribed annual maintenance procedures are a combination of engine parameter checks and adjustments, idle emission measurements, and visual (or functional) inspections and/or replacement of various engine and control system components. As in the case of idle test maintenance previously discussed, it is difficult without a dynamometer to correctly identify engine malfunctions that occur most pointedly at loaded-engine conditions. Reliable diagnosis of such malfunctions requires careful attention by mechanics and the use of test equipment that is not currently available at many garages. In developing such maintenance procedures, available malfunction-emission sensitivity and frequency of occurrence data, such as that given in Ref. 2-4, have been used to determine those component checks, emission measurements, and component replacements needed to correct malfunctions and maladjustments that occur with highest frequency and/or contribute the most to increased emissions. Refinement of specified maintenance procedures would continue in the future as more data become available on late model vehicles.

Because mandatory maintenance programs require the application of uniform maintenance procedures to all vehicles, some unnecessary repairs and parts replacements may result and in some cases may even cause an increase in emissions. A compromise program based upon inspection of specific engine and emission control system parts and adjustments reduces the tendency to over-repair while eliminating the need for purchasing emission measuring equipment. The elimination of direct emission measuring equipment is accomplished at the cost of a more extensive engine parameter inspection procedure.

## 2.4 EMISSION REDUCTIONS AND REPAIR COSTS OF ALTERNATIVE I/M APPROACHES

In this section, results obtained in various I/M field or experimental studies using alternative I/M approaches and fleets of in-use vehicles are reviewed, compared, and correlated. Of particular interest are the emission reductions achieved and the cost of repairing and/or servicing vehicles subjected to maintenance. The results discussed in this section are for a single inspection/repair cycle and do not include the effects of deterioration between inspections or the accumulative effect on average fleet emissions of repeated inspection/repair cycles.

### 2.4.1 Emission Reductions Obtained Using Alternative I/M Approaches

As indicated previously in Table 2-1, various I/M studies have been conducted using one or more alternative I/M approaches. The effectiveness in terms of emission reduction achieved of a particular I/M strategy depends on a number of factors including:

a. Emission inspection test used and its discrimination capability
b. Emission characteristics of the test fleet
c. Failure criteria and resultant failure rate
d. Repair/maintenance procedures
e. Thoroughness of instructions to mechanics
f. Limits on the extent of repairs permitted to failed vehicles

There often are significant variations in one or more of these factors, even between studies designed to compare the same two I/M approaches. This should be kept in mind in the subsequent comparison of both the emission reduction achieved and the cost of repair incurred for different I/M strategies. It is important also to note that emission reductions (even percent reductions) obtained using different emission test procedures (seven-mode hot start, idle, 1975 CVS-CH) should not be compared directly. In some studies, results of tests using one procedure have been compared with those using another by first applying a regression relationship determined by comparing the results of tests using both procedures on the same vehicles. This type of analysis can lead to false conclusions because in most instances the scatter in the data is quite large and the results of the two procedures do not correlate well even on a fleet average basis.

In comparing the effectiveness of various I/M approaches, it is convenient to do so at selected failure or rejection rates. Since there is only a single failure rate associated with each I/M study, the emission reduction effectiveness at other rejection rates (necessarily lower ones) is determined by analyzing a subset of the entire group of repaired vehicles from that program. It is assumed that the emission characteristics (before and after repair) of that subset are equivalent to those that would have resulted from lowering the rejection rate by changing the failure criteria. The accuracy of this assumption is difficult, if not impossible, to assess.

A final, but important, limitation on the quantitative results to be given in the following paragraphs is that they apply in a strict sense only to precontrolled (pre-1968) and controlled (1968-1971) vehicles that have not been previously subjected to an I/M program. As noted previously, vehicles with more advanced control systems and vehicles that have been inspected and maintained for several years may respond differently to a given I/M program than the vehicles included in the I/M studies whose results are being analyzed. Nevertheless, much has been learned from past I/M studies, and the results are important in evaluating alternative I/M strategies for future application.

The feasibility of an enforced mandatory tune-up requires the identification of specific engine components and adjustment parameters that have a significant effect upon vehicle emissions and whose malfunctioning can be predicted with a reasonable degree of certainty. The cost effectiveness of mandatory maintenance is highly sensitive to the identification of the optimal tune-up specifications for each engine component and the reliability of predicting the frequency of malfunction.

The test fleet used to evaluate this strategy was composed of pre-1966 vehicles representative of the domestic vehicle population in California. The repair action included the replacement of the major components in the secondary ignition system (spark plugs, spark plug wires, breaker points, condenser, and distributor rotor), the air cleaner filter, and the positive crankcase ventilation (PCV) valve, and adjustment of the idle parameters (air/fuel ratio, rpm, and timing). The estimated cost for the required parts and labor was \$55 per vehicle. A 15-percent average reduction of exhaust HC emissions and an 11-percent average reduction of CO emissions were observed following the tune-up of the entire sample fleet.* There was no significant change in the fleet mean $NO_x$ emissions.

Every vehicle in the test fleet received identical maintenance regardless of the as-received exhaust emissions. The total fleet average emissions after tune-up as a function of the percentage of vehicles receiving maintenance are shown in Figures 2-3 and 2-4. For this analysis, the vehicles were ranked according to the as-received (before tune-up) exhaust emissions; progressively larger fractions of the population were assumed to have been identified for maintenance using an emission test. Each percentile represents the highest emitters comprising that fraction of the test fleet.

As indicated in Figure 2-3, the maximum leverage for reduction of fleet HC emissions is obtained from the highest emitters composing 20 to 30 percent of the population. Carbon monoxide reductions improve linearly by increasing the maintenance fraction through 50 percent of the population. The maximum reduction of CO emissions would have resulted from repairing 80 percent of the vehicles.

Data obtained in the emission inspection study reported in Ref. 2-1 have been reviewed and compared in detail. Summaries of the data being compared are shown in Figure 2-5. Curves are given for the Idle Test and Key Mode inspection repair procedures discussed in Sections 2.2 and 2.3.

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*These emission reductions are based on limited data from an early test program. Later test results indicate that higher HC and CO emission reductions are achievable immediately after servicing.

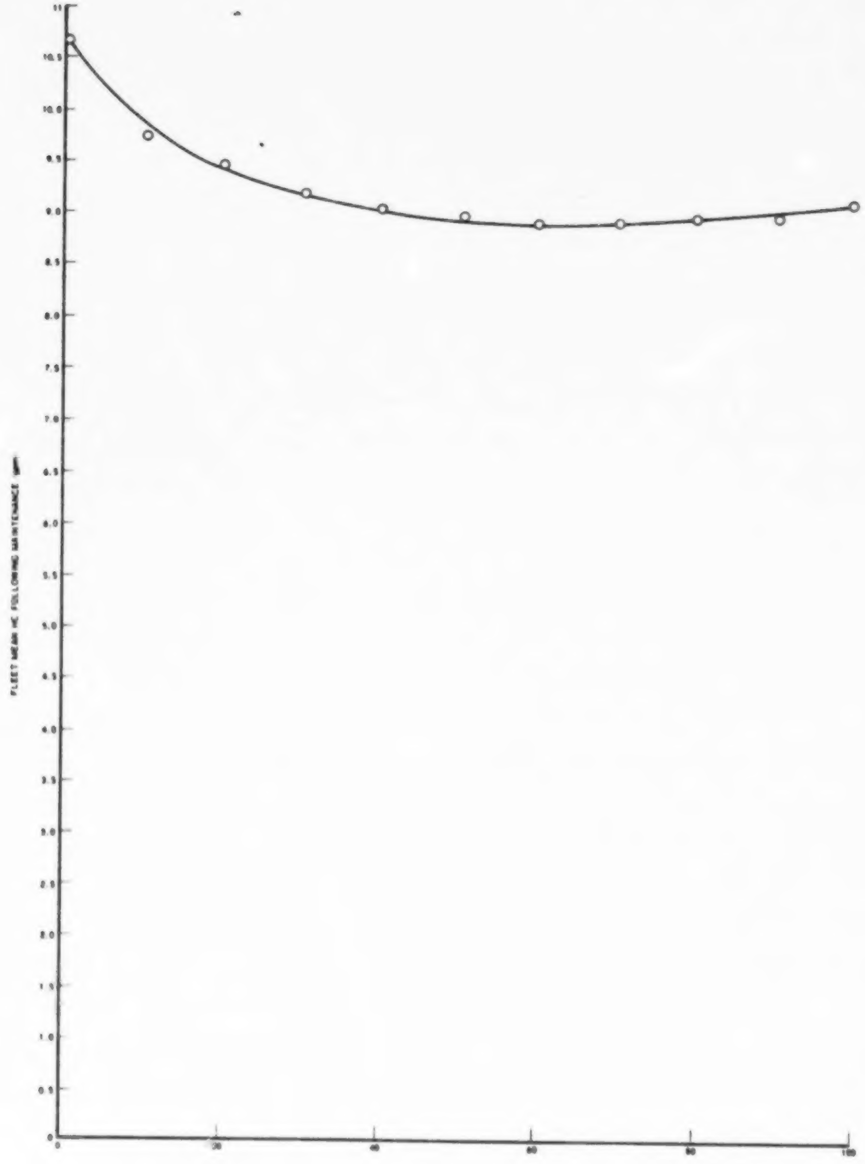


Fig. 2-3. Hydrocarbon Levels vs Population Percentage (Ref. 2-12)

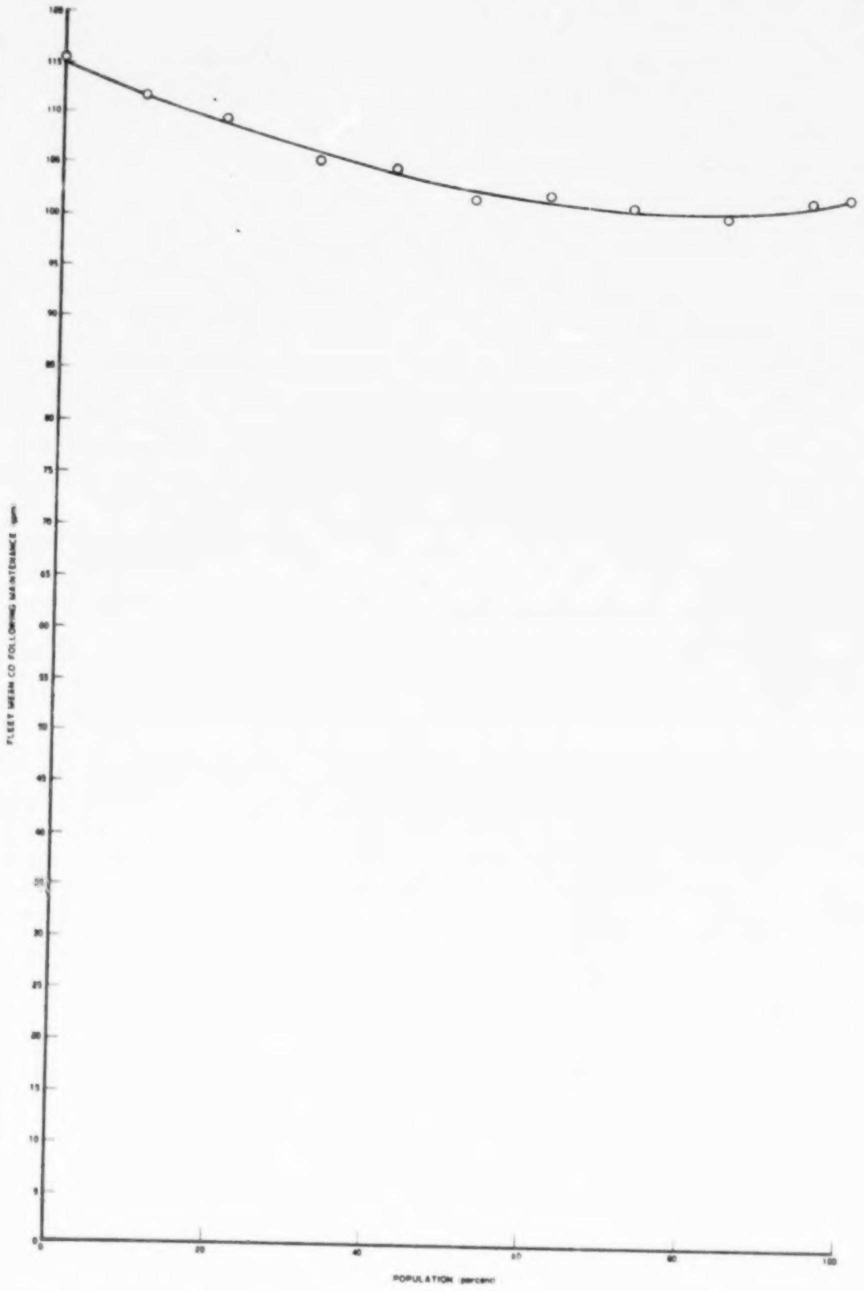


Figure 2-4. Carbon Monoxide Levels vs Population Percentage (Ref. 2-12)

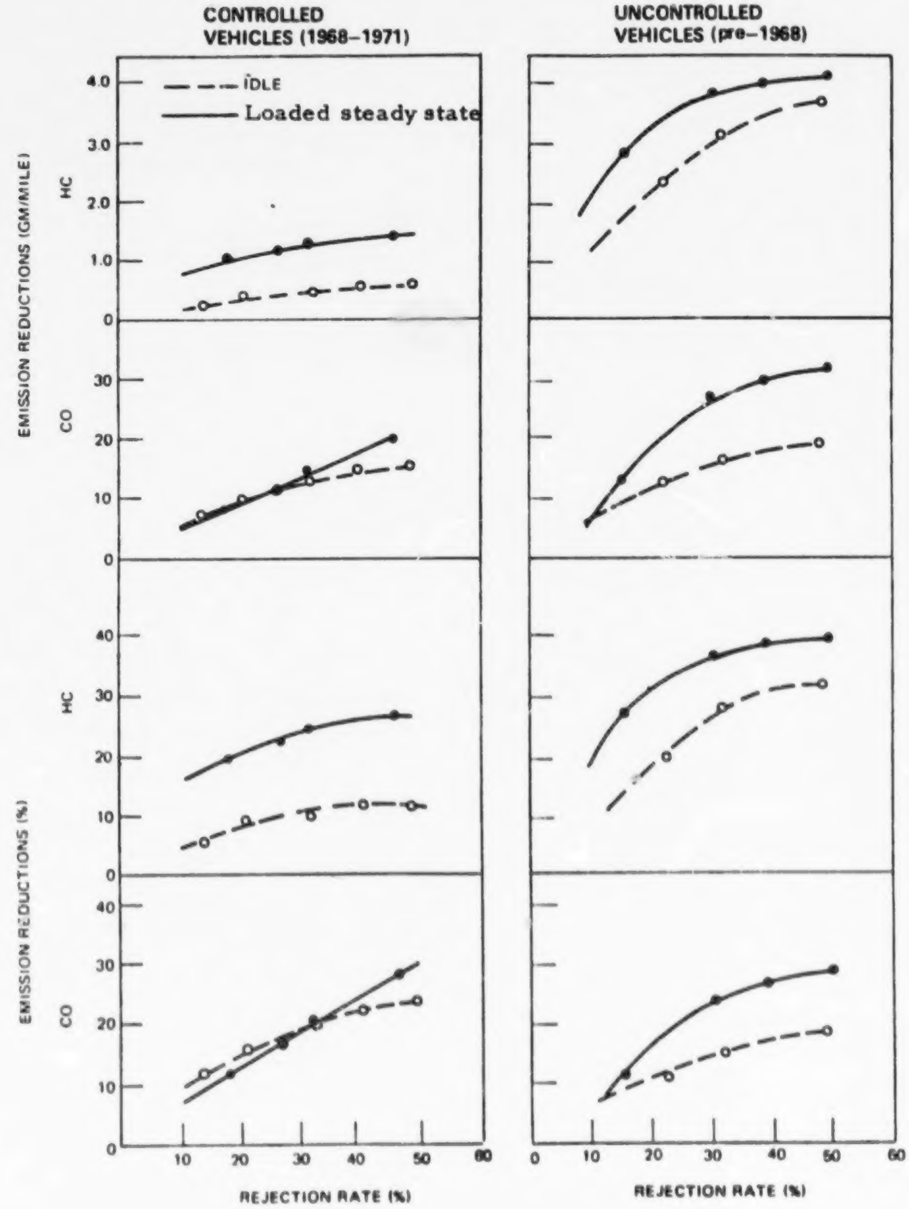


Figure 2-5. Emission Reduction Effectiveness as a Function of Rejection Rate (Phase II results of Ref. 2-1)

The data reported in Refs. 2-2 and 2-3 were obtained using the seven-mode, hot-start test procedure. The results for both controlled and uncontrolled vehicles are consistent with those shown in Figure 2-5 and indicate clear trends relative to the effect of failure rate and the effectiveness of the various alternative I/M strategies in reducing emissions after a single inspection/repair cycle. The major conclusions drawn from these analyses are the following:

a. The additional fleet emission reductions achieved by failing more than 50 percent of the fleet are small.

b. The Key Mode test/repair procedures have a clear superiority over the idle test/repair procedures in reducing fleet emissions at all failure rates.

### 2.4.2 Repair Costs for Serviced Vehicles

Repair cost data for vehicles serviced in the I/M study reported in Ref. 2-1 are summarized in Figure 2-6. The repair costs depend primarily on the scope of the engine adjustments and/or tune-up specified in the maintenance instructions to the mechanics taking part in the program and the average state-of-maintenance of the vehicles being repaired. There are, however, considerable variations in costs from program to program even for the same I/M approach and rejection rate due to differences in the ability of the mechanics to identify correctly the causes of the high emissions of the failed vehicles and to make only those repairs needed to reduce the emissions. The detailed maintenance procedures and truth charts discussed in Section 2.3 were developed to aid the mechanics in making more cost-effective, emission-oriented repairs. Detailed examination of the emissions data for individual vehicles taken before and after repair in all the I/M studies reported to date shows that in a significant number of instances the potential for large emission reduction was not realized even though the vehicle repair cost was quite high. As the repair industry becomes more accustomed to emission reduction as an important reason for vehicle repair and servicing, their performance in this regard should improve.

While there have been variations in costs between I/M studies, on the average simple idle adjustments on failed vehicles can be made for $5

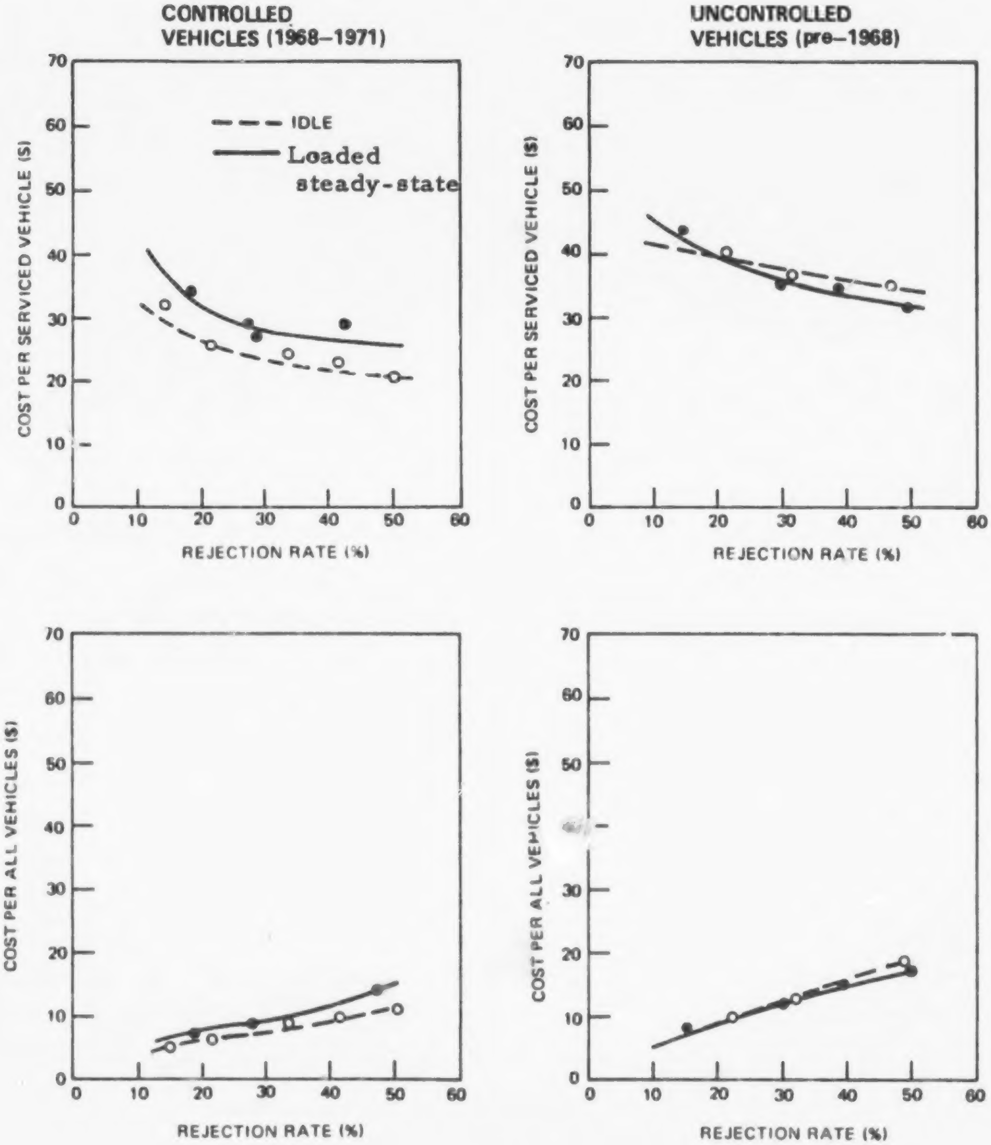


Figure 2-6. Average Vehicle Repair Cost (Phase II Results of Ref. 2-1)

or less, while a thorough minor tune-up costs between $25 and $35. When major repairs are needed or more extensive engine diagnostic measurements are specified, the repair costs are significantly higher. The average cost per vehicle repaired increases as the rejection rate is decreased. This is as expected, since the most out-of-repair vehicles are the ones that are rejected first and require more extensive work. In the other extreme of subjecting all vehicles to a specified tune-up regardless of their emissions levels, the average cost per vehicle is about $55 (Ref. 2-4).

## 2.5 DETERIORATION OF EMISSIONS WITH AND WITHOUT PERIODIC I/M

There are several aspects of the deterioration of emissions from in-use vehicles that should be considered in evaluating the net emission reductions to be expected from I/M strategies. First, what increase of emissions would occur for the various vehicle model years in the absence of a mandatory I/M program? Second, after a rejected vehicle with high emissions is repaired and its emissions reduced, what increase in emissions will occur prior to the next emissions inspection? Third, what emissions increase will occur in the vehicles that passed the inspection before they are subject to inspection again? It is the offsetting effects of the emission reductions due to the repair of rejected vehicles and the increase in emissions of both repaired and passed vehicles between emission inspections that determine the net emission reductions achieved by I/M strategies.

Emission deterioration can be expressed in terms of the fractional change per unit time (or mileage) or directly as the absolute change (gm/mi) per unit time (or mileage). The fractional change or deterioration factor approach has proved to be more convenient in studies of I/M because the absolute level of emissions for various classes (model year and control system) of vehicles in the population differ markedly (reflecting the changing Federal Emission Standards for new vehicles). In determining the deterioration factors for a given class of vehicles, one can either (1) average the deterioration factors of the individual vehicles of that class, or (2) average the emissions from a fleet of such vehicles taken at specified times or mileages and calculate the deterioration factors for the fleet from the change in the average emissions. The statistical character of emissions testing, vehicle repair, and the occurrence of malfunctions and maladjustments in engine and emission control systems results in the second approach being the most advantageous. Most of the deterioration-related information in the literature is presented in terms of deterioration factors obtained using averaged emissions data.

### 2.5.1 Deterioration of Emissions with Voluntary Maintenance

The exhaust emissions from vehicles tend to increase with time (or age), even when the manufacturer's recommended maintenance program is followed. Many vehicle owners have only that maintenance performed that they feel is needed to maintain good operating reliability and driveability of the vehicle. As indicated in Figure 2-7, the emission characteristics (gm/mi vs vehicle age) resulting from these limiting types of maintenance practices are significantly different. The objective of the I/M strategies is to reduce the deterioration of emissions with vehicle age so that the emission characteristics of in-use vehicles approach those that would result from following the manufacturer's recommended maintenance schedules.

### 2.5.2 Effective Emission Reductions Resulting from I/M Programs

The effective reduction in emissions that results from an I/M program is the difference between the average (annual) vehicle emissions after the program has been implemented and those emissions that would have occurred in the same vehicle population in the absence of the I/M program (i.e., with only normal voluntary maintenance). The effective emission reductions thus can depend on a large number of factors, including:

a. The average levels of emissions of the vehicle population prior to implementation of the I/M program.

b. The emission reductions achieved in the vehicle population subject to mandatory repair/maintenance.

c. The increase in the emissions of the maintained vehicles after repair and prior to the next inspection or mandatory maintenance period.

d. The increase in the emissions of vehicles not subject to mandatory maintenance or repair during an I/M period.

e. The potential for a general upgrading of the state of maintenance of the vehicle population due to repeated I/M cycles, and any accumulated emission reductions due to such upgrading.

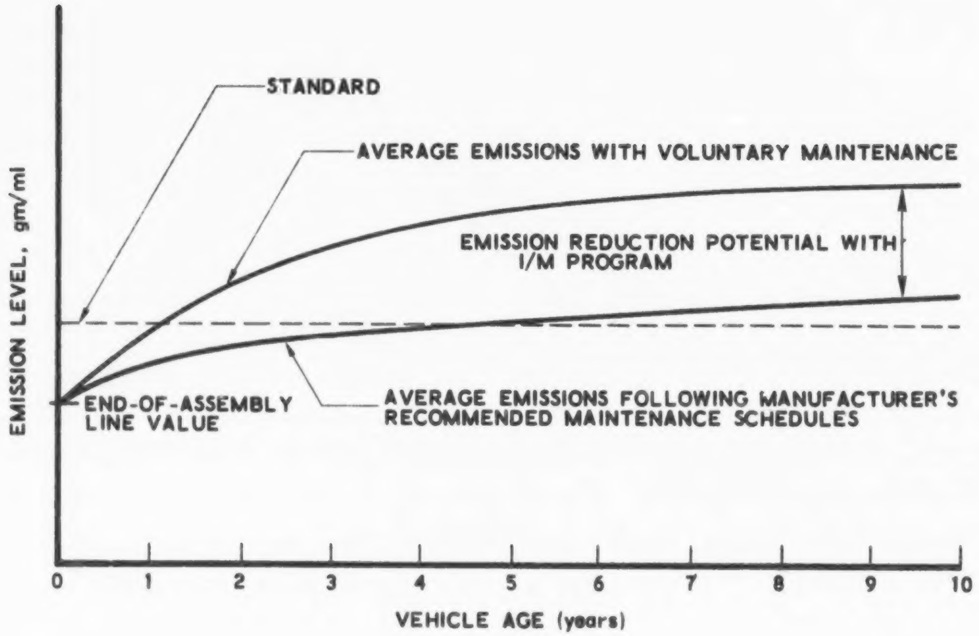


Figure 2-7. Effect of Maintenance on Emission Deterioration with Vehicle Age (Illustrative example only)

f. The effect of the existence of the I/M program on the maintenance practices of vehicle owners who are not required to have mandatory maintenance done during a given period.

g. The effectiveness of the I/M program and any associated training and licensing programs in bringing about a general improvement in the ability of the auto service industry to perform emission-oriented repairs/maintenance.

h. The effectiveness of the enforcement provisions of the I/M program with regard to compliance and prohibition of tampering between inspections.

The interactions between these various technical and socioeconomic factors are complex and difficult to evaluate quantitatively. Most of the relevant analytical work to date has attempted to include only factors a through e listed above. Factors f through h are of such nature that they are extremely difficult to include in an analytical model. In addition, it will take a number of years after the initiation of an I/M program before the actual net effect of all of these possible interactions is realized in a particular State or Air Quality Control Region (AQCR). Therefore, it is necessary to make initial estimates of the emission reduction effectiveness of the various I/M approaches when planning for I/M program implementation. Actual data taken during the I/M program proper can then be used to verify initial estimates or to adjust failure criteria to obtain the desired emission reduction levels.

A comprehensive and detailed quantitative evaluation of various I/M approaches has been made by TRW and reported in Ref. 2-4. In that work, the statistical character of the various engine and emission control system maladjustments and malfunctions present in the vehicle population is examined, as well as the effect on emissions of applying various inspection and repair/maintenance procedures. A computer program was developed to calculate the effects of the maintenance procedures on the various maladjustment/malfunction distributions of the serviced (rejected) vehicles over a period of years. One difficulty encountered in modeling the I/M processes was the nonlinear character of the response of the various engine maladjustments to the maintenance procedures and deterioration between inspection periods. The computer program developed by TRW is potentially a very useful tool for evaluating various I/M approaches; however, a systematic evaluation of the computer program itself has not been made to date.

A simpler approach to the problem of estimating emission reduction effectiveness than the computer model previously discussed would be to use estimating parameters for which data have been already obtained for at least a significant fraction of the vehicle population. For example, the change in the average emissions of a fleet of vehicles subjected to the I/M cycle (inspection, repair of rejected vehicles, and deterioration of both passed and failed vehicles prior to the next scheduled inspection) can be written as

$$\Delta E = E - E^{o} = PE_{L}^{o}(DP_{o} - 1) + (1 - P)E_{H}^{o}[(1 - RF)(DF_{o}) - 1] \qquad (1)$$

where

$\Delta E$ = net change in emissions over period between inspections

$E^{o}$ = average emissions at time of initial inspection

$E$ = average emissions at time of subsequent inspection

$P$ = fraction of vehicles passed

$(1 - P)$ = fraction of vehicles failed

$E_{L}^{o}$ = average emissions of passed vehicles

$E_{H}^{o}$ = average emissions of rejected vehicles

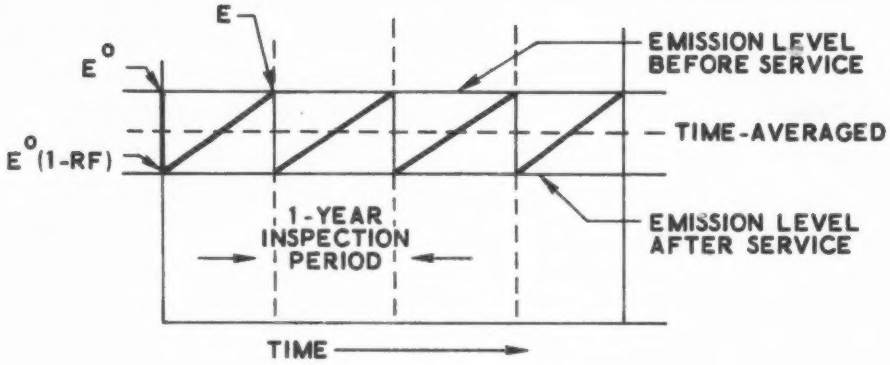
$RF$ = fractional reductions in emissions of serviced vehicles

$DP_{o}$ = deterioration factor of the passed vehicles for the period between inspections (emission level after the deterioration period divided by the initial emission level)

$DF_{o}$ = deterioration factor for serviced vehicles for the period between inspections (emission level after deterioration period divided by the post-tuning emission level)

This equation applies individually to each of the exhaust pollutants (HC, CO, and NO$_x$) and in principle describes adequately the effect of repeated I/M cycles, including deterioration, on vehicle emissions. However, adequate experimental data are not presently available to determine with reasonable confidence the reduction factor (RF) and the deterioration factors (DP$_o$ and DF$_o$) as functions of emission level $\left(E_L^o, E_H^o\right)$, especially after repeated I/M cycles. Therefore, it is necessary to either simplify the deterioration model such that detailed correlations are not needed or use "best estimate" correlations in the more complete model [Eq. (1)].

Because of these uncertainties and lack of statistical data, EPA currently utilizes a linear deterioration method. The key assumptions of the linear deterioration method are: (1) the emission reductions achieved by both voluntary and mandatory maintenance are essentially the same, and the primary effect of an I/M program is to subject additional vehicles to maintenance; (2) in the case of an annual inspection or mandatory maintenance program, the emissions of all serviced [illegible] voluntary and mandatory will deteriorate in a linear manner back [illegible] level they had before servicing, and (3) that assumptions (1) and [illegible] valid for all rejection rates. The time-history of the emissions from a typical serviced vehicle, consistent with these assumptions, is illustrated in the sketch below. The effective emission reduction (averaged over the one-year period between inspections and/or servicing) is then one-half of the average emission reduction achieved immediately after repair of a fleet of typical rejected vehicles. Thus, for each rejection rate, the effective emission reduction estimated using the linear deterioration method follows directly from knowledge of the average fleet emission reductions achieved in the I/M studies listed in Table 2-1. In other words, the effective emission reduction values for the various I/M approaches (idle test, loaded test, periodic mandatory maintenance, etc.) can be obtained by simply dividing the appropriate values of emission reduction achieved immediately after repair by two.



It is possible that the emission reductions predicted using the above linear deterioration approach may be found to be conservative when more I/M program data become available, because it does not account for any general upgrading of the state of maintenance of the vehicle population after repeated I/M cycles. Calculations made by TRW (Ref. 2-4) indicate that such a general upgrading may occur, particularly if the proficiency of the repair industry improves with time after the I/M program is implemented.

As noted previously, there have been various estimates of the effective emission reductions for HC and CO that can be expected using the various I/M approaches. All of the estimates are based in one way or the other on the limited available I/M study and emissions surveillance data. The reduction values that are estimated by EPA for I/M programs utilizing both idle and loaded test/repair procedures have been published in the Federal Register (Appendix N).* The EPA-estimated values for rejection rates between 10 and 50 percent are shown in Table 2-15.

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*"Appendix N - Emission Reductions Achievable Through Inspection, Maintenance, and Retrofit of Light Duty Vehicles" Federal Register, Vol. 38, No. 110 (Friday, June 8, 1973).

Table 2-15. EPA Estimated Emission Reductions for I/M Programs[a]

| Rejection Rate (%) | % Reduction | |
|---|---|---|
| | HC | CO |
| **Idle Emission Test** | | |
| 10 | 6 | 3 |
| 20 | 8 | 6 |
| 30 | 10 | 8 |
| 40 | 11 | 9 |
| 50 | 11 | 10 |
| **Loaded Emission Test** | | |
| 10 | 8 | 4 |
| 20 | 11 | 7 |
| 30 | 13 | 9 |
| 40 | 14 | 11 |
| 50 | 15 | 12 |

[a] Appendix N of 40 CFR 51 (Federal Register, Vol. 38, No. 110 (Friday, June 8, 1973)

It would appear that these values are reasonable estimates of average I/M program performance, particularly in the early years of a program when the auto service industry level of proficiency in making emission-oriented repairs is uncertain and the general state of maintenance of the vehicle population has not been upgraded to any extent. Data obtained during the course of pilot and/or full-scale I/M programs might indicate that the present EPA estimates of emission reduction are conservative and that greater reductions are achievable. On the other hand, less than full compliance, inadequate enforcement techniques, and poor repair proficiency during an I/M program could result in lower emission reductions than those projected by the EPA estimated values.

## 2.6 COST EFFECTIVENESS OF ALTERNATIVE I/M APPROACHES

### 2.6.1 Cost Effectiveness Criteria

The cost effectiveness of an emission control strategy can be described in terms of the pounds or tons of pollution controlled and the net cost paid by or in behalf of the public to administer and comply with the regulations and/or standards set by the program.* The term net cost means the actual cost of the labor and materials required by the program (including overhead and profit) and excludes any funds that are not expended for goods and services required by the program itself. In this report, all cost effectiveness values are given as dollar cost (labor and materials) per pound pollutant eliminated ($/lb).

Both the costs and the pounds of pollution eliminated should be calculated or averaged over the same base or reference period of time. Since the average fleet emission reductions in gm/mi may vary significantly from year to year as the I/M cycle is repeated, and since it is the cumulative effect of the program that determines its ultimate benefits, a 5-year period of repeated I/M cycles has been used as the reference or base period rather than the period (usually one year) between emission inspections.**

The total cost incurred is the sum of the cost of inspection and the subsequent repair of rejected vehicles, minus any fuel savings cost resulting from the improved state-of-maintenance of the vehicle population. The cost effectiveness is this cost divided by the total emission reduction over the same time period.

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*No attempt is made herein to attach a dollar value to such costs/benefits as better health, greater visibility, convenience, mobility, etc. The costs of training, surveillance, garage and mechanic licensing, and enforcement programs are not included as they vary widely from program to program and, in some cases, are omitted entirely.

**The 5-year period was used for cost amortization purposes only. The change in vehicle age distribution throughout this period was not considered.

### 2.6.2 I/M Program Costs

### 2.6.2.1 Inspection Costs

Determination of the inspection cost per vehicle for the various I/M strategies requires detailed consideration of the fixed and operating costs associated with the operation of emission inspection facilities, as well as the rate at which vehicles can be processed through the facility for different inspection procedures. Cost estimates given here are restricted to State-owned and operated lanes; only Idle and Key Mode emission inspection procedures are considered.

Component costs per lane are shown in Table 2-16 for the inspection building and grounds, emission measurement instrumentation, and annual operating expenses. The facility and instrumentation costs were prorated over a 15-year period, with 1/10 of the total cost being annualized to account for the interest factor. As shown, it is estimated that the annualized fixed plus operating costs per lane are about $55,700 per year for an idle emission inspection and about $56,500 per year for a loaded mode emission inspection. It is important to note that in developing these costs it was assumed that emission inspection was the sole function of the facility and that it was not added to or part of a safety inspection system. The values given in Table 2-16 may differ from EPA estimates previously presented as they represent updated cost information generated in 1974 by EPA.

In order to determine the inspection cost per vehicle, it is also necessary to know the average rate at which vehicles pass through the lane. Calculation of the inspection rate requires a number of assumptions regarding the time needed to conduct the emission measurements, the failure rate, and the fraction of the time that the facility is occupied. Estimated values for these quantities are given in Table 2-17.

The cost per vehicle inspected is obtained simply by dividing the total annual cost per lane by the average effective vehicle inspection rate. The inspection costs for Idle and Key Mode inspection are shown below for rejection rates between 10 and 50 percent.

Table 2-16. Emission Inspection Lane Costs

| Component Costs[a] | Test Procedure | |
|---|---|---|
| | Idle Test ($) | Key Mode Test ($) |
| Facility (not including instrumentation)[a] | 43,750 | 45,250 |
| Emission measurement instrumentation[c] | 13,360 | 19,360[b] |
| Annual operation[d] | 50,000 | 50,000 |
| Annualized fixed cost[e] | 5,711 | 6,461 |
| Total Annual Cost | $ 55,711 | $ 56,461 |

[a] Costs per test lane in a two-lane test facility.

[b] Includes variable power absorption dynamometer and associated instrumentation.

[c] HC, CO, $NO_x$ gas analyzers with semiautomatic readout; no $NO_x$ analyzer needed for idle test.

[d] Assumes a two-man operating crew for each lane with supporting facility and instrumentation maintenance, plus required supervision and administration.

[e] Initial facility and instrumentation costs are annualized as 1/10 of total each year (includes interest factor)

Table 2-17. Inspection Lane Utilization Data

| Item | Test Procedure | |
|---|---|---|
| | Idle Test | Loaded Test |
| Inspection time (minutes/vehicle) | | |
| Pre-test | 1.5 | 1.5 |
| Emission test | 1.0 | 2.0 |
| Post-test | 0.5 | 0.5 |
| Total | 3.0 | 4.0 |
| Average inspection time with two-man crew (minutes/vehicle) | 2.0 | 3.0 |
| Maximum vehicle inspection rate/lane | 30 vehicles/hr | 20 vehicles/hr |
| Inspection rate/year | 41,800 | 27,800 |
| Five 8-hr days/week | | |
| 67% occupancy factor | | |
| Effective inspection rate/year, including retests | | |
| 30% rejection rate | 32,200 | 21,400 |

| Failure Rate (%) | Inspection Cost ($)/vehicle Idle | Inspection Cost ($)/vehicle Key Mode |
|---|---|---|
| 10 | 1.47 | 2.23 |
| 20 | 1.60 | 2.43 |
| 30 | 1.73 | 2.64 |
| 40 | 1.86 | 2.84 |
| 50 | 2.00 | 3.05 |

#### 2.6.2.2 Maintenance-Related Costs

The maintenance-related costs that are of interest in evaluating the cost effectiveness of I/M programs are the expenditures required to repair rejected vehicles and the fuel savings resulting from the improved state-of-maintenance of the vehicle population due to the I/M program. Repair costs have been discussed previously in Section 2.4.2.

It is generally agreed that better maintenance of vehicles leads to improved fuel economy. Therefore, any fuel cost savings would partially offset the costs of inspection and repair incurred in a mandatory I/M program. Fuel savings due to the repair of the rejected vehicles are given in Table 2-18. These savings are based upon calculations using the standard carbon-balance method used by EPA to relate fuel economy and $CO_2$, CO, and HC emissions. The values in the table represent the average fuel savings at the time of the maintenance. If the assumption of linear deterioration to the pretuned condition over a one-year period used to determine the time-averaged emission reduction is applied to these fuel savings, they should be divided by two to determine the time-averaged fuel savings.

### 2.6.3 Comparison of the Cost Effectiveness of Various I/M Approaches

Cost effectiveness criteria and methods of determining the emission reductions from and the costs associated with various I/M approaches have been discussed in previous sections. These methods were used to

Table 2-18. Fuel Economy Changes of Repaired Vehicles

| Test Fleet | No. of Vehicles Repaired | Decrease in Fuel Consumption (gm/mi) |
|---|---|---|
| | | Carbon Balance[a] |
| California Key Mode (controlled, 1966-1971)[b] | 17 | 17.4 (7.5%) |
| California Key-Mode (uncontrolled, pre-1966)[b] | 22 | 22.5 (9.75%) |
| Michigan Key-Mode (controlled, 1968-1971)[b] | 15 | 12.8 (5.5%) |
| Michigan Key-Mode (uncontrolled, pre-1968)[b] | 16 | 24.1 (10.4%) |
| | 70 | 19.6 (8.4%) |

[a] 1972 CVS FTP used to obtain emissions data; ( ) % fuel savings based on 12 mpg, which is the approximate average fuel economy for the combined fleet.

[b] Data taken from Ref. 2-1.

calculate the emission reduction and cost effectiveness values given in Tables 2-19 and 2-20. Values are given in the tables for idle and loaded emission test/repair type programs, as well as for the mandatory maintenance type of program that has no separate inspection phase. The cost effectiveness ($/lb) is given both excluding and including the effect of fuel savings that result from the improved maintenance of in-use vehicles. These cost effectiveness values were determined by dividing the total per vehicle cost for a given emission control strategy by the corresponding values of per vehicle emission reduction for each emission specie (HC, CO). Thus they do not represent any attempt to prorate or apportion control costs among the vehicle emissions considered. Some other studies have reported cost effectiveness values that apportion control costs on an arbitrary basis (e.g., by assigning 50 percent of the per vehicle control costs to HC control and 50 percent to CO control, where a given control system reduces both HC and CO). For comparison with other study results, the values given in Tables 2-19 and 2-20 can be easily adjusted by apportioning control costs on the same basis as the study being compared.

For reject rates of less than 80 percent, the HC and CO emission reductions achieved both increase as the fraction of vehicles receiving mandatory maintenance increases; the cost effectiveness of the HC and CO emission control decreases as more vehicles are serviced. The cost effectiveness of I/M programs for reducing HC emissions varies in the range $0.20 to $1.50/lb, while the range for CO is $0.04 to $0.13/lb.

The results given in Tables 2-19 and 2-20 indicate that the loaded (Key Mode) test approach yields a greater emission reduction at a correspondingly better cost effectiveness than the idle test approach for both HC and CO emissions. It should be noted that all the cost effectiveness values given in the tables depend directly on the emission reduction and costs assumed for the various programs so that any change in emission reduction will change the cost effectiveness of a program proportionately.

As expected, the cost effectiveness of all the I/M programs is better for uncontrolled than for controlled vehicles. This is primarily due to

Table 2-19. Summary of I/M Emission Reduction and Cost Effectiveness for Idle Emission Test/Repair and Mandatory Maintenance

| Rejection Rate (%) | Hydrocarbon Emissions[a] | | | Carbon Monoxide Emissions[a] | | |
|---|---|---|---|---|---|---|
| | % Reduction[b] | Cost Effectiveness ($/lb) | | % Reduction[b] | Cost Effectiveness ($/lb) | |
| | | Excl. Fuel Savings | Incl. Fuel[c] Savings | | Excl. Fuel Savings | Incl. Fuel[c] Savings |
| Controlled Vehicles[d] (1968-1971) | | | | | | |
| Idle Test | | | | | | |
| 10 | 6 | 0.83 | 0.59 | 3 | 0.132 | 0.094 |
| 20 | 8 | 1.03 | 0.71 | 6 | 0.109 | 0.075 |
| 30 | 10 | 1.12 | 0.79 | 8 | 0.111 | 0.078 |
| 40 | 11 | 1.25 | 0.91 | 9 | 0.121 | 0.088 |
| 50 | 11 | 1.46 | 1.09 | 10 | 0.127 | 0.095 |
| Mandatory Maintenance | 13 | 4.04 | 3.67 | 12 | 0.347 | 0.315 |
| Uncontrolled Vehicles (pre-1968)[e] | | | | | | |
| Idle Test | | | | | | |
| 10 | 6 | 0.50 | 0.29 | 3 | 0.099 | 0.057 |
| 20 | 8 | 0.63 | 0.35 | 6 | 0.083 | 0.047 |
| 30 | 10 | 0.68 | 0.39 | 8 | 0.084 | 0.049 |
| 40 | 11 | 0.76 | 0.47 | 9 | 0.091 | 0.056 |
| 50 | 11 | 0.87 | 0.56 | 10 | 0.095 | 0.061 |
| Mandatory Maintenance | 19 | 1.48 | 1.21 | 14 | 0.199 | 0.162 |

[a] All emissions related to 1975 CVS FTP.

[b] All emission reduction values taken from Appendix N of 40 CFR 51 or obtained using the linear deterioration method.

[c] Fuel cost: $0.50/gal

[d] Average emissions from controlled vehicles: HC - 4.75 gm/mi, CO - 60 gm/mi.

[e] Average emissions from uncontrolled vehicles: HC - 8.9 gm/mi, CO - 90 gm/mi.

Table 2-20. Summary of the I/M Emission Reduction and Cost Effectiveness for Key Mode Emission Test/Repair Procedures

| Rejection Rate (%) | Hydrocarbon Emissions[a] | | | Carbon Monoxide Emissions[a] | | |
|---|---|---|---|---|---|---|
| | % Reduction[b] | Cost Effectiveness ($/lb) | | % Reduction[b] | Cost Effectiveness ($/lb) | |
| | | Excl. Fuel Savings | Incl. Fuel[c] Savings | | Excl. Fuel Savings | Incl. Fuel[c] Savings |
| Controlled Vehicles[d] (1968-1971) | | | | | | |
| 10 | 8 | 0.72 | 0.47 | 4 | 0.113 | 0.075 |
| 20 | 11 | 0.82 | 0.54 | 7 | 0.102 | 0.067 |
| 30 | 13 | 0.93 | 0.63 | 9 | 0.106 | 0.071 |
| 40 | 14 | 1.05 | 0.72 | 11 | 0.106 | 0.072 |
| 50 | 15 | 1.13 | 0.80 | 12 | 0.112 | 0.079 |
| Uncontrolled Vehicles[e] (pre-1968) | | | | | | |
| 10 | 8 | 0.42 | 0.21 | 4 | 0.084 | 0.042 |
| 20 | 11 | 0.49 | 0.25 | 7 | 0.077 | 0.039 |
| 30 | 13 | 0.56 | 0.30 | 9 | 0.080 | 0.043 |
| 40 | 14 | 0.63 | 0.35 | 11 | 0.080 | 0.044 |
| 50 | 15 | 0.67 | 0.39 | 12 | 0.083 | 0.048 |

[a] All emissions related to 1975 CVS FTP.

[b] Emission reduction values taken from Appendix N of 40 CFR 51

[c] Fuel Cost: $0.50/gal.

[d] Average emissions from controlled vehicles: HC - 4.75 gm/mi, CO - 60 gm/mi.

[e] Average emissions from uncontrolled vehicles: HC - 8.90 gm/mi, CO - 90 gm/mi.

the fact that uncontrolled vehicles have higher emission levels than controlled vehicles and the percent emission reductions achieved by maintenance are at least as high for the uncontrolled vehicles as for the controlled vehicles. Cost of maintenance does not seem to vary much between the two vehicle groups.

## 2.7 I/M PROGRAM IMPLEMENTATION CONSIDERATIONS

In selecting which of the I/M approaches is most advantageous for a given State or AQCR and then in planning for the timely and effective implementation of the selected I/M strategy, a wide variety of technical, social, and economic factors must be considered and appropriate administrative and legislative decisions made. For example, Table 2-21 lists the major steps that would be involved in the eventual implementation of a full-scale I/M program. This delineation of major steps represents the case where a State (or AQCR) has not yet begun or completed initial planning and tradeoff studies, and includes a pilot (or demonstration) program phase prior to implementation of the full-scale I/M program. Each of the major steps of Table 2-21 is discussed in detail in later sections.

These discussions do not address any aspects of tradeoff studies or other activities related to comparisons of candidate emission reduction measures within the overall area of transportation control strategies (e.g., retrofit, gaseous fuel conversion, control of hydrocarbon refueling emissions, traffic control, etc.). For purposes of discussion, it is assumed that these studies and comparisons have been made and that it has been determined that an I/M program is either necessary or advantageous in order to meet the emission reduction requirements of the area in question.

Technical information and other assistance is available from EPA to aid States or other government agencies involved in planning for I/M program implementation. Therefore, EPA should be contacted (through the appropriate office) to obtain other available or supplementary information not contained in this report.

### 2.7.1 Initial Planning and Tradeoff Studies

A number of initial planning and tradeoff study activities are required to assess and evaluate those factors whose characteristics could affect:

a. The success or failure of the program
b. The emission reduction effectiveness of the program
c. The costs and cost effectiveness of the program

Table 2-21. Major Steps Involved in Implementation of I/M Program

- Initial Planning and Tradeoff Studies
    - Selection of Basic I/M Approach
    - Relationship to Other Existing or Planned Programs
    - Training, Licensing, and Quality Control Aspects
    - Enforcement and Vehicle Owner Requirements
    - Coordination Between Involved Agencies
    - Program Planning and Cost Estimation
- Development and Passage of Enabling Legislation
- Engineering and Administrative Studies
- Pilot Program Construction and Procurement
- Pilot Program Operation
- Planning for Full-Scale Program
- Full-Scale Program Construction and Procurement
    - Recruitment and Training
    - Manpower Development
- Full-Scale Program Operation
- Ongoing Licensing and Quality Control Program
    - Public Information Program

In addition, such preliminary studies are needed to identify any special test program activities that should be a part of the pilot I/M program or which should be conducted prior to the pilot program.

Also, there are numerous broad administrative and legislative policy decisions concerning the specific I/M approach selected that must be made before it is possible to consider the management and implementation of the program in detail. These policy decisions, for the most part, can significantly affect the impact of the program on the citizens involved and thus influence their acceptance of it. As a consequence, the attitude and support of legislators regarding the program can be affected also. In most cases, a general discription of the I/M program, together with the specification of many policy-oriented provisions, would be expected to appear in the enabling legislation. Thus, the information resulting from the initial planning study is necessary to enable the drafting of effective enabling legislation.

In Sections 2. 1 through 2. 6, the data and information that are currently available have been summarized for use in initial planning and tradeoff studies related to I/M approaches for light duty vehicles. The major factors and considerations that should be treated in the initial study phase are discussed and highlighted in the following sections (2. 7. 1. 1 through 2. 7. 1. 6).

### 2.7.1.1 Selection of Basic I/M Approach

There are basically two types of I/M programs to consider. One type involves the inspection/repair sequence in which only vehicles rejected in some type of emission and/or engine parameter inspection are repaired. The other type involves a periodic maintenance of all vehicles regardless of their emission levels or state of maintenance. This second type of program may be simpler and less costly to administer because it requires only the specification of maintenance procedures and some method of checking that they are being followed by the automotive repair industry. In effect, the mechanic who does the maintenance is also the inspector. While this is a simplifying step, it could result in more maintenance being performed than is needed to achieve the desired control of emissions from the in-use vehicle population. In the inspection/repair type of program, the State would be involved with the inspection phase of the program, as well as the specification of repair procedures and supervision of the repair industry. The setting of inspection rejection rates and the associated failure criteria are two of the most difficult aspects of establishing such an I/M program. In addition, if the inspection is done in State-owned and operated lanes, the State must finance the initial capital costs for land, buildings, and equipment, and determine satisfactory locations for the inspection sites.

Other approaches to providing inspection are to have it done in private garages as is customary for safety inspections in many States, or to have a random highway inspection performed by specially trained officers using mobile equipment. These latter two means of inspection involve less initial costs to the State than inspection lanes, but also are less effective in consistently identifying high emitters and/or poorly maintained vehicles. Whether it is practical to perform the inspection in private garages and/or at mobile sites on streets and highways depends to some extent on the type of test procedure to be used. For example, an idle test can be performed rather easily in a private garage or at a mobile site, but a loaded test requiring a dynamometer might be restricted to inspection lanes.

Deciding between the use of the idle and loaded test inspection procedures has proved to be a source of considerable discussion. The relative simplicity of the idle test and the ease with which it can be done without expensive equipment in private garages and service stations have been the primary reasons for its being favored by the repair industry. The relative complexity of the I/M process, its statistical character, and the large variation in the performance of the mechanics in the repair phase of the I/M studies conducted to date have tended to make it difficult to quantify the relative advantages of loaded test procedures over the idle test. However, where the two procedures have been compared, the loaded mode procedure has been shown to be from 15 to 40 percent more effective than the idle mode procedure in reducing HC and CO emissions.

Because of the several basic I/M options available and the impact of the choice of I/M program on emission reduction levels, costs, etc., the process of identifying and selecting the basic I/M program approach considered most appropriate for any given State or AQCR should encompass the analysis and tradeoffs of a number of factors.

### 2.7.1.1.1 Selection of Vehicles to be Included in Program

A major factor affecting both program scope and emission reductions to be expected is the fraction of the vehicle population (by model year and type) to be included in the program. In this regard, a trade-off analysis that compares the cumulative I/M emission reductions of potentially included vehicle classes (e.g., pre-1968, 1968 to 1969, 1970 to 1972, etc.) vs the motor vehicle emission reductions required in the State or AQCR to meet prescribed air quality standards may be necessary to justify the inclusion of specified vehicle groups. However, in the New Jersey idle mode I/M program, all in-use light duty vehicles are required to participate. Even new car dealers are required to verify (via an idle emissions test) that all vehicles sold meet the required emission levels of the I/M program.

Another category of consideration in planning an I/M program involves how vehicles of differing age (model year) and level of emission control are to be treated in the program. Because of the progressively tightened new vehicle emission standards over the past years, there is a wide variation in the emission levels and emission control systems on vehicles currently in use. Both inspection failure criteria and maintenance/repair procedures should reflect these differences. Where insufficient surveillance test data exist to adequately characterize expected I/M emission reductions, it may be necessary to implement special vehicle test programs to provide this information. An alternative course of action would be to make the best possible estimate (based on similar data from EPA, other States, etc.) and to provide for verification of the estimate during the pilot or demonstration phase of the overall program.

### 2.7.1.1.2 Selection of Regional or Statewide Approach

Another major factor that similarly impacts both program scope (and costs) and emission reduction benefits is the decision as to regional or statewide applicability of the I/M program. Obviously, one key factor to be considered in this decision option is how many AQCRs within a given State require I/M emission reductions to meet air quality goals, and what portion of the State's vehicles are located and/or used within the confines of these specific AQCRs. If a sufficiently large percentage of the vehicle population of the State (of the relevant vehicle groups) are directly involved, it could be argued that statewide applicability would be both expedient and equitable. On the other hand, if only a single AQCR were directly involved with motor vehicle emission reduction requirements, it could be argued that statewide applicability would be nonequitable and would incur costs not necessary to meet air quality requirements.

The issue of "fairness," whether it be one of requiring everyone to share the same burden with respect to I/M program requirements and costs or be one of requiring participation only to the extent required by air quality considerations, can be a major problem with regard to passage of legislation. For example, consider the case of a State that had only one county requiring a rollback in motor vehicle emissions. Residents of this county might feel it unfair to permit vehicles from other counties to enter their area unless they, too, were participating in the I/M program. The residents of the other counties might not want to participate in an I/M program since the air quality in their counties does not require it; on the other hand, they might prefer to participate in the program in order to have the benefits of even cleaner air. Thus, the legislator is faced with balancing many and perhaps conflicting interests in enacting legislation for an I/M program.

In either of the above two hypothetical cases, consideration should also be given to the possible methods of program enforcement (see Section 2.7.1.4 below) and their possible impact on resultant I/M emission reductions. For example, restriction of I/M program applicability to a single AQCR (or other regional subdivision) requires an enforcement technique which assures that the appropriate vehicle classes or groups within the region are indeed participating in the I/M program if I/M emission reduction benefits are to be in fact achieved. In addition, there are instances where a single AQCR encompasses land situated in more than one State, thus further complicating the enforcement problem (as well as complicating the overall problems associated with I/M program initiation). In these cases, parallel or joint programs involving two or more States may be required in order to realize the air quality gains from I/M program implementation.

### 2.7.1.1.3 Selection of Idle or Loaded Mode of Testing

Various cities and/or AQCRs have proposed implementing I/M programs with either idle or loaded emission testing. Although the loaded testing mode appears to have advantages in terms of emission reduction and cost effectiveness ($/lb of pollutants reduced), the idle testing mode offers advantages in the areas of simplicity of the test, lower program start-up capital costs, lower equipment costs for repair garages, and greater ease of combining emission I/M with existing safety I/M programs. Thus the proper choice of idle vs loaded testing for a given city, State, or AQCR should be based on consideration of a number of factors. These include:

a. Mobile source emission reductions required to meet air quality standards

b. Possibility of combination of emission I/M with an existing safety I/M program

c. Availability of capital funds for program start-up

d. Previous experience in the licensing and supervision of the auto repair industry.

Each of these factors is discussed further in the sections that follow.

### 2.7.1.1.3.1 Equipment Requirements

Development of emission controls has been closely related to the availability of instrumentation and equipment for conducting emission measurement tests. Because of this, a reasonably full range of emissions measuring instruments, computers, dynamometers, and engine parameter analyzers are available to the States and the service industry. Within each of these catagories a number of manufacturers are producing a variety of models to satisfy the need of specific I/M programs. Consequently, a large number of good instruments are now available. For example, Table 2-22 lists the infrared analyzers for HC and CO currently approved by New Jersey for use in repair garages in connection with that State's idle inspection program. Other lists are available. Although there is presently a lack of low-cost $NO_x$ measuring instruments and very low range HC and CO analyzers for use with post-1974 emission controlled vehicles, past experience indicates that such equipment should become available as the need increases.

### 2.7.1.1.3.2 Facility and Land Requirements

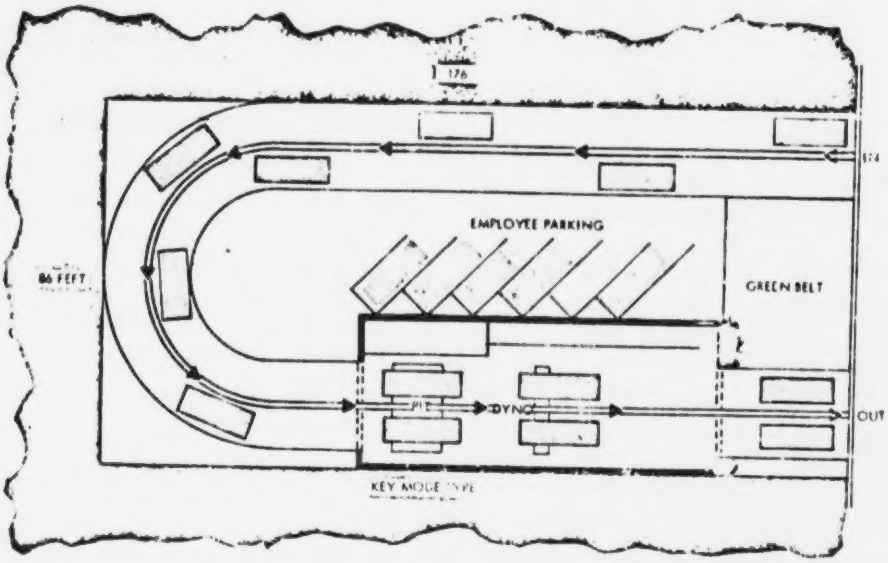
The number of inspection facilities (and land) required depends not only upon the selection of regional vs statewide applicability but also upon the vehicle inspection processing rate associated with the specific inspection test procedure selected and whether or not the emission I/M program is to be combined in any way with an existing safety I/M program.

Detailed planning studies for implementing I/M programs have been performed for several States. These studies have included the layout of the inspection building and grounds and the estimation of the number and location of the inspection lanes throughout the States. For example, sketches of both an inspection lane and a mobile test unit for the Key Mode loaded test inspection procedure are shown in Figure 2-8. The number of test lanes required depends on the vehicle population density and the rate at which vehicles can be processed through an inspection facility of either the idle or loaded test procedure. Mobile inspection units could be used to inspect vehicles in rural areas where a low vehicle density perhaps would not justify building an inspection station. The information found in Refs. 2-14 and 2-15 may be useful to aid in the preliminary planning of inspection facilities, but current vehicle population data for the specific region of interest (city, State, AQCR) would have to be used to determine the number

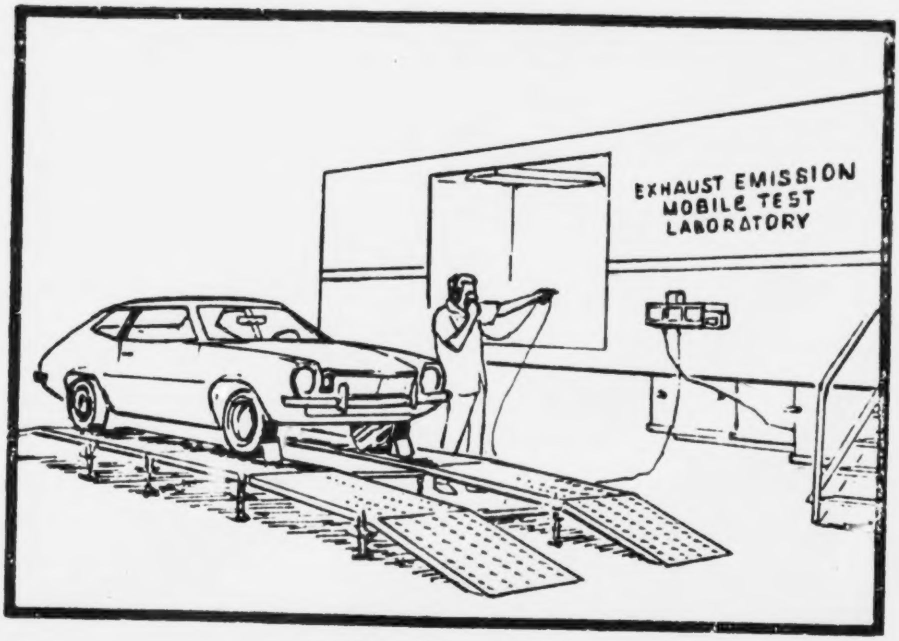
Table 2-22. New Jersey-Approved Manufacturers of Low Cost Infrared Analyzers Suitable for Use in Repair Garages (Ref. 2-13)

| Supplier | Model |
|---|---|
| Allen Electric Company | Emission Analyzer Model 23-060 series and 23-070 series |
| American Motors Corporation[a] | AMserv Model 23-067 series and 23-077 series |
| American Parts Company | Powerready Infrared HCKO Analyzer Model 370-400 |
| Atlas | Exhaust Emission Tester Model 340 |
| Autoscan, Incorporated | CO and HC Analyzer Model 710 and 4030 |
| Barnes Engineering Company | Emission Analyzer Model 8335 |
| Beckman Instrument Company | HC/CO Vehicle Emissions Analyzer Model 590 |
| Chrysler Corporation | Technican Service Equipment Program; Model DCE-75, 23-066 series and 23-076 series |
| Ford Motor Corporation | Rotunda Equipment Program; Rotunda Analyzer Model BRE-42-730 and BRE-42-731 |
| Kal-Equip | HC/CO Infrared Emissions Analyzer Model 4094-C |
| Marquette Manufacturing Corporation | Emissions Analyzers Model 42-151 and 42-153 |
| NAPA Balkamp | Infrared HC/CO Emissions Analyzer Model 14-4787 |
| Horiba Instruments Limited | Engine Exhaust Analyzer Models CSM-300 and Mexa-300 |
| Peerless | Infrared Exhaust Gas Tester Model 600 |
| Stewart-Warner | Infrared Gas Analyzer Model 3160-A |
| Sun Electric Corporation | Sun EET-910, U-912, U-912-I, and EPA-75 Exhaust Emission Testers |
| Womaco-Yanaco | Exhaust Gas Analyzer Model EIR-101 |

[a] Available only in new car dealers of the company.


176
174
EMPLOYEE PARKING
86 FEET
GREEN BELT
PIT
DYNO
OUT
KEY MODE TYPE

Double-Lane Configuration


EXHAUST EMISSION
MOBILE TEST
LABORATORY

Mobile Test Facility

Figure 2-8. Key Mode Double-Lane Configuration and Mobile Test Facility

and location of inspection stations needed in that region. In addition, the potential of combining emission and safety I/M programs could greatly affect the number of inspection facilities required.

### 2.7.1.1.3.3 Emission Reduction Effectiveness

One of the most important characteristics of any I/M program is the reduction achieved in emissions from serviced vehicles. The test procedure used in the I/M program can affect the emission reduction achieved in at least two ways. First, the relative ability of the test procedures to consistently identify those vehicles that would have high emissions if they were tested using the Federal Test Procedure. Such vehicles can potentially benefit most from repair. Second, the ease with which the average mechanic, after reasonable training on making emission-related repairs, can use the emission inspection results as an aid in correctly diagnosing the cause of high emissions in a particular vehicle. The I/M studies to date have shown that the loaded test procedure is superior to the idle test procedure when the failure criteria used rejected the same fraction of vehicles and when the mechanics in both programs were instructed with the same thoroughness. Of course, the superior emission reduction effectiveness of the loaded test procedure has to be balanced against its more severe requirements in the areas of equipment, facilities, costs, etc. In many cases, it may not be necessary to utilize the loaded test procedure where desired emission reductions can be obtained with the less effective, but simpler, idle test procedure.

### 2.7.1.1.3.4 Flexibility With Regard to Advanced Emission Control Systems

Consideration should be given to whether or not the selected inspection test procedure will be appropriate for use as additional groups of vehicles are added to the I/M program (e.g., vehicles with $NO_x$ control and/or oxidation catalysts, etc.). In this regard, the idle test procedure is not applicable for $NO_x$ emission inspection. There is insufficient data to ascertain whether or not idle tests are appropriate for catalyst-equipped cars; however, the low exhaust flow rates at idle would argue against it applicability. Loaded test procedures are required for $NO_x$ emission inspection and are expected to be suitable for catalyst-equipped cars.

### 2.7.1.1.3.5 Costs and Cost Effectiveness

Both costs ($) and cost effectiveness ($/lb of pollutant eliminated) can be key factors in selecting the most advantageous emission inspection test procedure. With regard to cost, one should consider both the inspec- and repair costs. The inspection fee (which might be in the range of $1 to $3 per vehicle tested) is relatively small compared with the registration fee for the vehicle and the repair bill for rejected vehicles regardless of which short test procedure is used. The major difference in the inspection costs, as they affect the choice between loaded and idle tests, is in the initial capital (start-up cost) that is needed to set up the inspection lanes and/or inspection phase of the program. Even though the equipment costs per lane are only slightly greater for a loaded test, the primary factor in increasing the initial capital requirements for the loaded test is the fact that the loaded test takes much longer to perform and hence the number of inspection lanes needed to inspect a given number of vehicles using the loaded test is about 50 percent greater than using the idle test. Thus the magnitude of the initial funding needed to start an I/M program using a loaded test can be nearly twice as large as that needed using the idle test, when both the increased number of lanes and more expensive equipment are considered.

The time required to perform the emissions test is so short that it can even be added to a safety inspection lane without significantly effecting the testing rate. This has been done successfully in New Jersey with a minimum additional cost. In California, an idle test for emissions has been added in a similar manner to the random highway safety inspection program conducted by the highway patrol. This would not have been practical using a loaded test, however, because of the need for a chassis dynamometer, which is a bulky piece of equipment. Thus, in determining costs for implementing an emission I/M program, the possibility of integrating it with an existing safety I/M program can greatly affect the costs associated with the overall program. This consideration can also affect the decision regarding loaded vs idle test procedures.

The cost effectiveness of an I/M strategy depends both on the costs incurred and the emission reduction achieved for that cost. When the loaded and idle test procedures are compared on this basis, the loaded test approach is usually superior because the repair costs from both approaches are almost the same and much greater than the inspection cost. Also, the emission reductions achieved using the loaded test/repair procedures are significantly greater than those achieved using the idle test/repair procedures. Hence, the loaded test approach yields a significantly greater emission reduction at only slightly higher cost to the consumer. This may also be true even in a state such as New Jersey, which has an established lane-type safety inspection program. In that case, however, the differences in the initial start-up costs of the loaded vs idle programs were so large that it would have been difficult to use a cost effectiveness argument to justify the loaded test approach.

#### 2.7.1.1.4 Selection of Rejection Rates and Failure Criteria

The primary objective of the inspection phase of the I/M program is to determine which vehicles in the total population have high emissions that can be reduced by proper maintenance/repair. Failure criteria can be set for each of the candidate short test procedures such that a specified fraction of the various classes (precontrolled, controlled, etc.) of vehicles inspected are rejected. The basic assumption is that the rejected fraction of vehicles would also have the highest emissions if they were tested using the Federal Test Procedure (FTP). Inspection data taken in various I/M studies have indicated that on the average the assumption relative to loaded and idle tests and FTP emissions is valid but that a fraction of the rejected vehicles have lower FTP emissions than some of the vehicles passed by the short test procedure (errors of commission). This results in the required repair of vehicles with relatively low FTP emissions. Also, a fraction of the passed vehicles have higher FTP emissions than some of those rejected (errors of omission). In this case, vehicles that actually require maintenance to reduce emissions are simply not identified. Experience in the I/M studies conducted to date have indicated that, at least for rejection rates up to about 80 percent, even those rejected vehicles which in a strict sense would be classified as errors of commission have relatively high emissions that can be significantly reduced by repair. Hence, in nearly all the I/M studies using both the idle and loaded test procedures, significant average emission reductions have been achieved in the serviced (rejected) vehicles.

On the basis of available data, the errors of commission appear to be somewhat less for the loaded test than for the idle test (especially for CO). Also, it would be expected that the loaded test would have fewer errors of omission (passing vehicles with high emissions) than the idle test, because it utilizes emission results from additional engine operating modes. In addition, the loaded test can detect vehicles with high $NO_x$ emission while the idle test can not.

In any event, the initial failure rate must be selected in order to estimate the number of failed vehicles and their impact on repair facility requirements, emission reductions, costs, etc. It may be necessary, or prudent, to conduct additional fleet test programs to acquire more test data or, in the alternative, to plan for such data acquisition in the pilot phase of the I/M program. Such data can be used to revise failure criteria for later phases of on-going, full-scale I/M programs. For example, in the New Jersey I/M program, the initial failure criteria were established to fail about 10 percent of the vehicles that were tested. More stringent emission failure standards were planned for subsequent years of the program.

Considerable care will have to be exercised by inspection personnel as vehicles subject to different failure criteria are inspected. In addition, it is likely that the rejection rate will be higher for older vehicles (higher mileage), which are in many cases owned by those less able to bear the cost of repair. The problem of how to handle the cases of high-mileage vehicles that may need costly repairs before they can pass the emission inspection has been the topic of considerable discussion. One approach to providing an equitable solution to this problem is to limit the maximum repair cost for emission reduction that must be borne by the vehicle owner to some percentage of the market value of the vehicle.

### 2.7.1.1.5 Retest Requirement Provisions

Another consideration in planning an I/M program is whether or not to include a requirement for retest of failed (rejected) vehicles after repair. Such a requirement impacts not only the total number of inspections to be made in a given period of time but more importantly the quality of the repair work done on rejected vehicles and thus the emission reduction effectiveness of the program. Without a retest, there is no assurance that the repair was done properly and that the vehicle emissions were actually reduced. Obviously a privately operated inspection program would be more prone to excessive repair costs, incomplete repairs, direct sale of inspection stickers, and other fraudulent practices that result in higher costs to the public and lower benefits to air quality.

In order for an I/M program to have public acceptance, it is important that the vehicle owners be confident that the repair work and/or periodic maintenance that they are paying for is done properly and will result in the desired reduction in emissions. It is essential that rejected vehicles after being repaired pass any emission retest with high probability. Repeated failures would result in considerable public complaints even if the program provided some type of guarantee of rework at no additional cost by the repair industry. It may be necessary to provide for an exemption procedure for those few vehicles that are inherently high emitters and will not pass the emission inspection even after proper repair and adjustment. In this latter case, it should be noted that there could be difficulties in identifying such vehicles and that several inspection-repair-retest cycles could be involved.

A retest requirement also impacts on the general problem of program evaluation (record keeping) and enforcement. These aspects are discussed in a later section.

### 2.7.1.1.6 Private vs State-Operated Inspection Facilities

Inspection facilities can be characterized under two general classifications: State-operated and licensed private garages. The State-operated inspections could be conducted in a system of State-owned or franchised inspection lanes in which all vehicles would be checked periodically (say annually) or at random sites on streets and highways by specially trained officers using mobile equipment. If the random inspection approach were used, only a fraction of the vehicles would be checked during each inspection period. In a licensed garage system, the emissions testing would be performed by private service or repair agencies within the automotive maintenance industry. Each such facility would have to be certified, licensed, and supervised by an appropriate State or local agency.

In either case, private service garages and dealerships comprising the automotive repair industry would provide the requisite maintenance. Although the selection of one approach over the other may not conceptually have an impact on the effectiveness of an I/M program, it would have a substantial effect on (1) who provides the initial capital investment, (2) how operating costs are determined and collected, (3) the relative difficulty in providing effective enforcement for the program, and (4) public acceptance of the program.

Public opinion surveys have shown that vehicle owners strongly prefer a State-owned and operated inspection lane system with only the maintenance being done at private garages. In comparing the two approaches, it would appear easier to maintain uniform and consistent inspection standards and equipment calibration if the inspection is done by the State. In addition, enforcement of compliance by vehicle owners and supervision of the repair industry may be simpler if the State performs the inspection phase of the program. The problem of program evaluation is also more easily handled if the State obtains the emission inspection data directly at its facility. For more complex inspection test procedures that require more expensive equipment, the arguments become stronger for a State-owned and operated system of inspection lanes. Hence, the arguments for State-operation of loaded test inspection lanes are stronger than for State-operation of an idle test, which can also be done at a private garage or at random inspection sites. On the other hand, such direct State involvement requires additional State manpower, new or revised organizations, increased funding, and expands the role of the State into a new form of work.

### 2.7.1.1.7 Data Acquistion and Record Keeping

Another factor that must be considered is the degree or extent of data acquisition and record keeping to be incorporated in the program. Once an I/M program has been implemented, the program must be monitored and information reported to Federal, State, and local agencies, as appropriate. The State and local agency reporting requirements will vary in detail and content between States and according to the type of I/M program implemented.

The evaluation of the effect of an emissions I/M program on automobile emissions and air quality requires the compilation of exhaust emissions data over a period of time (probably years). If the I/M program includes an emission inspection phase conducted by the State, the inspection data itself can be recorded, stored, and analyzed to determine the effect of the program on vehicle emissions. A special effort will be needed and expense incurred, however, to use the inspection phase to evaluate the program, as well as identify the vehicles needing repair. It will be necessary to relate the short test procedure values to those based on the Federal Test Procedure (1975 CVS-CH) for purposes of emission inventory calculations and comparison with new vehicle emission standards. (EPA is currently examining the correlation characteristics of a number of short test procedures.) Analysis of the inspection data is also required to update the failure criteria needed to yield the desired rejection rates. In those cases in which a separate inspection phase is not included in the program or inspection is done in private garages, evaluation of the I/M program will require periodic automobile surveillance emission tests in various sections of the State. At the present time, California is the only State that conducts such surveillance tests of automotive emissions. This later approach of obtaining emissions data for program evaluation may be simpler and more cost effective even for those States having a separate inspection phase; however, a much smaller sample of vehicles will be tested and questions may arise regarding the adequacy of the sample size and composition (type, make, and model year of the vehicles tested).

Thus on the one hand, if records of all emissions tests performed (including retests) are desired in order to (1) assure the necessary statistical basis for determining the actual emission reductions being accomplished, and (2) provide the data necessary to make meaningful adjustments in emission test failure criteria as the program progresses, such data acquisition and record keeping can be both time consuming and costly, as well as require very large data storage facilities. On the other hand, it may be acceptable to operate the program and evaluate emission reductions with less detailed data acquisition and record keeping measures. Thus, it is apparent that careful consideration should be given at the outset to this very important factor - the compilation and retention of data and test records. For example, it may be both necessary and cost effective to consider an electronic data processing system to perform the data collection and retention function. If so, it may require equipment interfaces that impact both inspection equipment selection and facility design.

### 2.7.1.2 Relationship to Other Existing or Planned Programs

If the city or State has, or plans to have, other vehicle-related programs, such as safety-inspection programs or emission control retrofit programs, it would appear both necessary and expedient to consider the impact of one program on the other and potential interfaces, including the possibility of combining functions and requirements. For example, if a safety inspection program incorporated the use of dynamometers for testing brakes, it might be possible to select a single dynamometer that is adequate for emissions and brake testing, thus permitting that portion of the safety inspection program to be combined with the emission inspection program.

Also, in the case of retrofit programs, similar equipment, facilities, and testing techniques may be appropriate.

Today, 32 States have some form of periodic motor vehicle safety inspection, and 8 additional States employ a spot check safety inspection system. Only New Jersey, Delaware, and the District of Columbia operate their own inspection stations; the remaining States use licensed private garages. The Pennsylvania statewide vehicle safety inspection program can be used to illustrate potential interactions and their ramifications. In the Pennsylvania safety inspection program, private garages are licensed to perform the necessary vehicle inspections. Such individual garages could also perform the inspection and maintenance phases of an I/M program if the idle inspection testing mode approach were adopted in that State. However, if the loaded inspection testing mode were selected, it is unlikely that the private garages would or could acquire the necessary dynamometers; therefore, the State would have to provide the necessary inspection test facilities, probably in the form of inspection lanes.

In any event, where such similar programs exist (actual or planned), the potential for combining the programs should be evaluated in terms of potential savings in consumer time, costs, and minimization of land use. However, in the case of private garage vs State-provided inspection facilities, there is the additional consideration, as noted previously, of customer acceptance of private garages for inspection purposes.

### 2.7.1.3 Training, Licensing, and Quality Control Considerations

One concern relative to the implementation and effectiveness of I/M programs is that the automotive repair industry may not be capable of performing cost-effective, emission-oriented repairs on the vehicles rejected in the inspection phase of the program. Inadequacies in the repair industry could lead to reduced effectiveness of the program and, if rejected vehicles are retested after repair, to vehicle owners experiencing the frustration and expense of repeated failures. If the I/M program involved emission testing in private garages or facilities, similar reservations would apply. Hence, licensing and supervision of the automotive repair industry by a State agency should be considered in regard to the implementation of all I/M programs.

Since the implementation of any form of an I/M program will result in a significant increase in automotive maintenance/repair services needed by the public, it is essential that these services can be obtained conveniently and at a reasonable cost. Thus the implementation of the program should also insure the availability of a sufficient number of repair garages and mechanics and a relatively uniform demand for the services over the year.

Various studies (Refs. 2-3 and 2-14) have been made of the scope and length of instruction needed by mechanics to enable them to make emission-oriented repairs and engine tuneups. All of the field studies (Refs. 2-1 through 2-4) of I/M have found that the emission reductions achieved by repair were dependent on the thoroughness of the instruction given the participating mechanics. It has been also found that the certification and standardization of exhaust gas analyzers are important. Both California (Ref. 2-16) and New Jersey (Ref. 2-17) have set design and performance criteria and accreditation procedures for HC/CO analyzers to be used in vehicle emission repair stations.

### 2.7.1.3.1 Instruction of Mechanics on Making Emission-Oriented Repairs

All of the I/M studies conducted to date have shown that unless the mechanics involved in the program had received thorough instruction on what engine malfunctions and maladjustments can result in high HC and CO emissions, and how various engine diagnostic tests can be used to isolate which of the possible malfunctions is present in a particular vehicle, the emission reductions achieved by the repair of rejected vehicles is much less than the potential reductions. The most beneficial instruction included actual demonstrations of how various malfunctions increased emissions using vehicles and exhaust gas analyzers. Supplying mechanics with written material and relying on written examinations to indicate that the material has been read was not nearly as effective as shop demonstrations. It has also been found that having mechanics perform routine maintenance on vehicles without providing instructions relating the various steps in the maintenance procedures to emission reduction results in only a minimal emission reduction. Actual measurements of emissions at as many engine operating modes as available equipment permits was found to be the best procedure, even in a mandatory maintenance program.

The subjects of the sensitivity of emissions and various engine and control system malfunctions and maladjustments, related diagnostic tests, and required equipment are discussed in detail in Section 2.3.1. In addition, various repair/tune-up and mandatory maintenance procedures are given in Section 2.4.1. Regardless of whether the I/M program to be implemented is of the inspection/repair type or the mandatory periodic maintenance type, it is necessary that the mechanics involved be knowledgeable concerning these topics. Otherwise experience has shown that in most cases repair/maintenance costs will be relatively high and the emission reductions achieved will be quite low.

#### 2.7.1.3.2 Certification of Exhaust Gas Analyzers

Experience has shown that the availability of reliable exhaust gas (HC/CO) analyzers is critical to the success of any I/M program. Since the implementation of an I/M program creates a relatively large market for such instruments, many of them have been developed with prices ranging from several hundred to several thousand dollars. As would be expected, the capabilities of these instruments vary significantly with respect to sensitivity, accuracy, response time, warm-up time, etc. In order to attain a high level of quality control on the repair/maintenance work done by the private garages and good relatability between emission inspection and repair industry emission measurements, it is necessary to set minumum specifications that must be met by all HC/CO analyzers used in an I/M program.

Both New Jersey and California have conducted gas analyzer certification programs and have made available approved lists of instruments to mechanics and service station operators. Specifications were set in the following areas:

a. Range
b. Sensitivity
c. Accuracy and repeatability
d. Ease and reliability of calibration
e. Drift in calibration
f. Response time and hang-up
g. Warm-up time
h. Maintenance requirements

Insuring that the exhaust gas analyzers used in the repair industry are properly maintained and calibrated will not be a simple task. Random spot checks by inspectors or local police may be necessary.

### 2.7.1.3.3 Mechanic/Garage Licensing and Quality Control

A number of States currently have on-going programs in the area of mechanic/garage certification, licensing, and quality control. In California, the Bureau of Automotive Repair (BAR) is a part of the Department of Consumer Affairs and licenses both motor vehicle pollution control (MVPC) installation and inspection stations and device installers. All legally required MVPC retrofit devices must be installed or approved by a licensed installer, and employment of a licensed installer is a requirement for licensing of a station. Approximately 11,000 stations have been licensed after BAR inspection visits to verify employment of a licensed installer and to verify that the necessary tools and equipment are available. Device installers are required to pass a multiple-choice written examination and to provide verification of competence, either in the form of a recommendation by the station licensee or by evidence of satisfactory training (from school, device manufacturers, etc.).

In Pennsylvania, the Bureau of Traffic Safety (BTS) is a part of the Department of Transportation and is involved in a vehicle safety inspection certification program. Approximately 17,000 official inspection stations have been licensed to date. As in the California MVPC program, the principal requirements are employment of a licensed mechanic and the availability of tools and equipment. The mechanics are required to take a training course and pass a written examination, as well as a practical test in vehicle safety inspection. Approximately 70,000 mechanics have been certified to date.

New Jersey has had a mandatory vehicle emissions inspection program in effect since February 1974. However, there was no pre-existing mechanic certification program. At present, the New Jersey Department of Environmental Protection (DEP) is supporting an informal voluntary program for training mechanics in the practical, hands-on aspects of emission control systems. Efforts are underway to expand this program, possibly involving the certification of mechanics.

Therefore, it would appear prudent to examine the training, licensing, and quality control aspects of these on-going State activities, as well as EPA programs in these areas, for consideration with regard to similar requirements in an I/M program. On the other hand, many competent individuals may prefer to do their own repair work, and some consideration may have to be given to their situation.

### 2.7.1.4 Enforcement and Vehicle Owner Interfaces

A number of conceptual approaches are possible to ensure compliance with an I/M program, including use of existing or modified car registration procedures, control of car dealers, and car inspections.

#### 2.7.1.4.1 Vehicle Registration

Since all States require annual registration of new and used cars, a preregistration requirement that owners of cars to be used in controlled regions show compliance appears relatively straightforward.

Unfortunately, existing registration procedures in most States are not capable of being used without some modification. In particular:

a. Very little effort is made to ensure that all cars are in fact registered, nor are penalties for late registrations severe. Enforcement is primarily through normal police or highway patrol traffic activities, such as stopping cars for speeding and reckless driving and in reporting and investigating accidents.

b. Although all States require an address for car registration, none is able to verify that such an address exists, and an applicant's legal address is not required. For purposes of car registration, a mailing address, post office box, second home, or business address are all valid.

c. Only California requires that emission control compliance (Equipment Installation Verification) be shown prior to registration.

Thus, to use existing State car registration procedures for ensuring compliance with an I/M program, expansion of State enforcement capabilities would be required, as in the example of California.*

### 2.7.1.4.2 Dealer Control

While enforcement of new car emission levels is a function of the Federal EPA, dealer control can be an effective enforcement tool for controlling emissions of used cars at the time of change of ownership. In this approach car dealers could be required to verify that all cars being sold are in proper operating condition and properly equipped for the region in which they will be operated. Difficulties with this approach are:

a. Most dealers are poorly equipped to determine their customer's legal residence or the primary area in which the car would be used.

b. New legislation with strong enforcement provisions might be required to ensure dealer compliance.

c. Fleet-car buyers who normally purchase and register in one area for use in another might be required to register locally.

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*In many states, all vehicle licenses expire at the same time, which makes it difficult to incorporate a timely inspection with the purchase of a new annual license. In such cases, a staggered licensing procedure that would allow 1/12 of the licenses to expire each month would be helpful.

### 2.7.1.4.3 Vehicle Surveillance

All cars in a given controlled region might be inspected periodically or randomly to ensure that they are participating in the I/M program. Such inspections could be physical in nature or be one of observation of a windshield or license plate color or number-keyed tag or sticker issued by an I/M inspection facility. Thus, a number of procedures are possible for ensuring successful compliance with an I/M program, including tying compliance to car registration, providing compliance through controls over car dealers, and enforcing compliance through car surveillance procedures. However, if widespread compliance is required, implementation of these procedures will call for additional State legislation and expansion of State enforcement agencies.

### 2.7.1.5 Coordination Between Involved Agencies

As can be noted from the preceding discussions, the management services required in the implementation of an I/M program may involve the responsibilities and expertise of several State (and/or municipal) agencies or departments. For example:

a. One agency may be charged with overall I/M program management responsibility.

b. The Department of Motor Vehicles (or other agency involved with vehicle registration) may be involved in compliance assurance.

c. Police departments (State and/or local) may be involved in physical inspections to assure compliance.

d. An environmental protection or air quality agency may be involved to establish the inspection procedures and standards and to determine results of the I/M program on air quality.

e. A separate agency may be involved in the training, licensing, and quality control activities.

f. Etc.

Thus, it is imperative that the efforts of all included agencies or departments be carefully coordinated in the planning and operation of an

I/M program to ensure program success. In California, for example, Senate Bill 479 makes such provision for interagency cooperation and sharing of management responsibilities.

Some further insight into management of an emission I/M program can be gained from looking at how States with safety I/M programs have managed those programs. In most States having safety I/M programs, management of the program is centered in the Department of Motor Vehicles. The enforcement function, both with respect to compliance of vehicle owners and the investigation of complaints against licensed private inspection/repair garages, is handled by the State Police. Public dissatisfaction with the automotive repair industry has led in some states to the establishment of Consumer Affairs Agencies within the State government to further license and supervise the repair industry. Management of emission I/M programs should not be significantly different than the management of safety I/M programs.

### 2.7.1.6 Program Planning and Cost Estimation

As a concluding part of the initial planning and tradeoff study activity, it is necessary to estimate program costs, select a method for financing the program, and prepare a time-phased program plan. These efforts are based on and thus include all the tradeoffs and resultant choices and decisions as discussed in Sections 2.7.1.1 through 2.7.1.5.

As noted previously, the initial and operating cost requirements will vary with the inspection test procedure selected and the number, type, and location of inspection facilities reduced. In general, however, an inspection fee of between $1 and $3 would be required to defray the cost of the emission inspection. This fee could be collected at the time of the inspection or as an added vehicle registration fee. Adding the fee to the vehicle registration fee removes the money-handling function from the inspection station, which may tend to reduce the incidence of inspector pay-offs. The initial cost of building and equipping the inspection stations could be covered by State bonds that would then be repaid using part of the revenue from the inspection fee.

An example of a time schedule for implementing State-owned inspection lane programs using idle or loaded-mode tests is presented in Figure 2-9. The actual times required to accomplish each of the tasks shown will vary greatly from one program to another. The times shown in the figure are typical and are for the purpose of illustration only. The time scale starts from the point where legal authority and funding are granted, and the acquisition phase is based upon the assumption that no facilities exist at that time. The 14 months allowed for facilities and equipment acquisition could be reduced if suitable test sites were readily available. If a great deal of red tape is involved in acquiring land, this acquisition period could be increased. Although the time to train inspectors can be predicted relatively easily, the hiring of technically competent people at all levels can be a major variable. Pilot studies lasting from 3 to 6 months can provide not only an opportunity to try out the proposed program but also a chance to obtain valuable data on pass-fail criteria and other technical aspects of the test procedure. Since it is more efficient from the viewpoint of both inspection and maintenance to stagger participation over the full inspection cycle period, at least one cycle must be allowed before the total benefits of an I/M program can be realized.

Similar schedules can be constructed for licensed garage programs, but again the extreme variability of the time required to complete many of the tasks should be kept in mind in doing so. Each I/M program should be treated separately in this respect, and predictions should be based upon the best available data for the specific program under consideration.

### 2.7.2 Development and Passage of Enabling Legislation

Passage of appropriate enabling legislation is, of course, a necessary and key milestone in the implementation of an I/M program, and a considerable period of time can be involved in assuring that such legislation adequately treats all aspects of the desired I/M program. To remedy this situation, the EPA has prepared model I/M legislation formats that should greatly assist the States in this important element of I/M program inplementation.

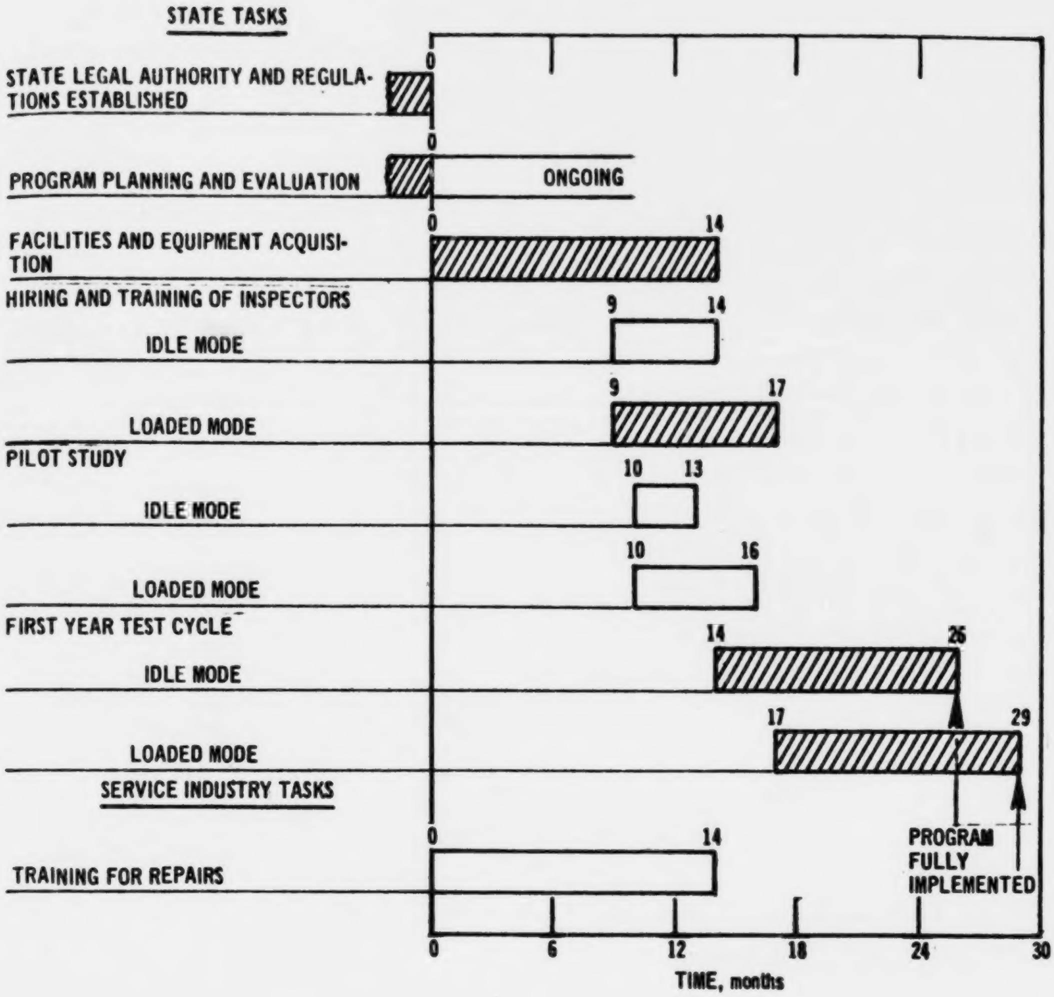

Figure 2-9. Estimated Time Required for Implementation of State-Owned Inspection Lanes Using Idle or Loaded Mode Tests. (Shaded bars represent critical path of tasks leading to full implementation.) (Ref. 2-13)

In the meantime, enabling legislation for I/M programs has been prepared and passed by the legislatures in several states. New Jersey, Arizona, Chicago, and California are a few examples. The New Jersey legislation provided for a statewide Idle Inspection Program that was combined with the existing safety inspection program done in State-operated lanes. The California legislation provided for a demonstration Loaded Inspection Program to be initiated in selected counties of the State. The Arizona bill provides for State lane loaded mode inspections conducted by a private contractor. The Chicago ordinance establishes idle mode inspection in city-owned and operated facilities. All cases of the I/M legislation passed to date treated special situations and hence none can be thought of as a model to be followed in preparing future enabling legislation for I/M programs. However, each bill provides an insight into what level of detail is likely to be required. This is especially true of Senate Bill 479 in California, which reflects the past experience of the California Legislature in preparing legislation for automotive retrofit programs for emission control.

In the general case, however, the conduct of initial planning and tradeoff studies, as discussed in Section 2.7.1, should result in the identification of the technical, social, and economic characteristics of the desired I/M program, thus enabling appropriate administrative and legislative policy decisions to be the basis for structuring effective enabling legislation. The socioeconomic impact of legislation dealing with motor vehicles is so great that legislators are reluctant to authorize such a program unless they have clearly in mind what is involved and can judge how the public is likely to react to it.

In this regard, some of the provisions that should be considered for incorporation in enabling legislation are:

a. Adequate authority to adopt rules and regulations concerning:

    1. Requirements for periodic inspection
    2. Establishment of fees for providing the inspection service

    3. Withholding vehicle registration for those vehicles that do not satisfactorily complete the inspection or that do not comply with an applicable variance
    4. Prohibition of tampering

b. Provisions for providing adequate funds for implementing, monitoring, and enforcing the I/M program

c. Adequate authority to obtain pertinent data and information, and require periodic reporting of emission information

d. Authority to make emission reports and information available for public inspection

e. Authority to compel compliance with rules and regulations, supported by civil or criminal penalties

f. Provisions for injunctive relief where deemed necessary

### 2.7.3 Engineering and Administrative Studies

Following adoption of the enabling legislation, it is necessary to perform definitive engineering and administrative studies in order to actually carry out the legislative mandate. These studies are now program-specific (i.e., concerned only with the specific I/M program adopted by the legislature) and are concerned with the details of program implementation. As such, they are an expansion of the initial planning studies and result in final decisions as to the management and enforcement structure of the program, specific sizes and locations of inspection stations, cost and financing procedures, etc. A key output of this study period is the identification and adoption of the pilot or demonstration phase of the overall full-scale program in sufficient detail to permit construction of the inspection stations and procurement of equipment.

Also, a program for information transfer to the affected vehicle owner, including details of requirements levied upon vehicle owners and compliance assurance measures to be used, should be implemented at this time. Because of the relatively recent advent of emissions as an important consideration in vehicle operations, the effect of maintenance and repair on auto emissions is much less well understood and easily recognized by the public than the effect of maintenance on safety. Hence, enforcement of compliance with emission I/M is likely to be more difficult than for safety

I/M, and the public is more apprehensive regarding the quality and cost of emission-related repair/maintenance services. For these reasons, the consumer affairs aspects of the implementation of emission I/M programs are even more important than for safety I/M programs. For example, both California and New Jersey have and continue to expend large efforts on the consumer affairs areas of educating the public on the relationship between vehicle emissions and maintenance and the licensing, training, and supervision of emission-related repair services and personnel.

By the end of this study period, the I/M program management group should be functional, and all participating State agencies (e.g., State or municipal police, air quality boards, motor vehicle groups, etc.) should be involved with program coordination activities.

### 2.7.4 Pilot Program Construction and Procurement

In this phase of the program, those inspection stations involved in the pilot program are constructed and the necessary measurement and recording equipment is procured, in accordance with final decisions made previously (Section 2.7.3).

Facility construction and equipment procurement should be monitored to assure that initially selected plans and designs are indeed adequate for program needs. Where changes are required, this information should be incorporated into the structure of the final full-scale I/M program by the management staff.

### 2.7.5 Pilot Program Operation

Operation of the I/M program on a pilot or demonstration basis provides the opportunity to verify the adequacy of facilities and equipment, observe personnel training requirements, finalize test and data acquisition procedures, and verify the operability of selected compliance assurance measures.

With regard to data acquisition, data taken in the pilot program can be used to adjust rejection rates and/or failure criteria, examine the desirability of the retest option, and preliminarily assess the degree of emission reduction afforded by the I/M program. Also, initial testing may indicate that record-keeping formats or procedures selected initially may on the one hand be too lengthy or otherwise cumbersome and costly, or on the other hand be inadequate or insufficient for purposes of emission reduction records of compliance assurance.

The training requirements of inspection facility personnel can be finalized by direct observation under actual working conditions (i.e., working with real vehicles, vehicle owners, and actual measurement and recording equipment).

Any problems that occur in the pilot program can be resolved, and any required modifications for the overall, full-scale I/M program can be structured into the full-scale program with a minimum impact on cost and time considerations.

### 2.7.6 Planning for Full-Scale Program

Final planning for the full-scale I/M program should proceed hand-in-hand with the operation of the pilot program. All potential problems discovered in the pilot program should be resolved within the framework of the full-scale program, and modifications to management structure, enforcement procedures, and facilities incorporated as appropriate to benefit the full-scale program.

The planning should consider to what extent the introduction of the full-scale program should be time phased in order to budget investment costs and operating costs within funding allocation limits. Such time-phased plans are required also to assure the availability of trained inspection facility manpower.

During this phase of the program, the adopted licensing program for garages and mechanics should be initiated in order to assure an adequate supply of trained mechanics and repair facilities when the full-scale program is initiated. This effort would also include the certification of approved emission measurement equipment.

### 2.7.7 Full-Scale Program Construction and Procurement

In this phase of the program, the remaining inspection stations are constructed and measurement and recording equipment is procured, in accordance with the initial program plan and any changes occasioned by problems or improvement areas discovered in the pilot program construction and operation phases.

Of particular importance in this phase of the program is the implementation of the training program and the adequate training of the personnel who will man the inspection stations.

### 2.7.8 Full-Scale Program Operation

Full-scale implementation of the overall I/M program is the final step or program phase. It is the culmination of all activities, commencing with the initial planning and tradeoff studies, and extending through the pilot program activities and final construction and manning of the complete I/M station network. It is the final product of the enabling legislation, and its success or degree of effectiveness is largely dependent upon the throughness with which all preceding steps have been made.

### 2.7.9 Ongoing Licensing and Quality Control Program

Concurrent with I/M program activities, per se, are a number of ancillary activities that also are critical to the success or failure of the program. As discussed in Sections 2.7.1.3 and 2.7.1.4, these activities include the implementation of selected procedures or techniques for licensing garages and mechanics, as well as adoption and implementation of a viable mechanism/organization for assuring quality control of the licensing process. Of equal importance is the establishment of effective techniques for keeping the public informed as to their requirements as vehicle owners and as to measures being enforced under the I/M program to meet the public's needs in the areas of air quality and effective vehicle maintenance procedures.

## 2.8 I/M OF HEAVY DUTY VEHICLES

### 2.8.1 Introduction

In Sections 2.3 through 2.7, the I/M of light duty vehicles was discussed in detail. The light duty vehicle category presently includes all vehicles with a GVW of less than 6000 lbs. In this section, various aspects of the I/M of vehicles with GVW greater than 6000 lb will be considered.* The percentages of in-use trucks in the nation in the various weight classes are shown in Table 2-23. The data given in the table were obtained from sales and truck registration information contained in Ref. 2-18. Note that over 60 percent of the trucks have a GVW less than 6000 lb; hence, they are presently classified by EPA as light duty vehicles** and must satisfy the same emission standards (gm/mi) as passenger cars. Starting with model year 1975, the emission standards for light duty trucks (GVW < 6000 lb) will be higher than passenger car standards. This section of the report is concerned with the other 35 to 40 percent of the trucks with GVW greater than 6000 lb. As shown in Table 2-23, about 50 percent of this group of vehicles fall into the 6000 to 10,000 lb weight class, with the remaining vehicles distributed in weight classes up to and exceeding 33,000 lb. Current Federal emission regulations for the heavy duty vehicles (GVW >6000 lb) are given in terms of emission standards for the engines to be used in those vehicles rather than for the vehicles themselves. Hence, for heavy duty vehicles, it is the engine rather than the vehicle that is certified by EPA. The engine emission tests are performed on an engine dynamometer using test cycles and procedures specified by EPA (Refs. 2-19 and 2-20). The heavy duty engine emission standards for both gasoline-fueled and diesel engines are

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*Mostly trucks, but there are increasing numbers of recreation vehicles (motorhomes and campers) that fall into this category.

**Starting in 1975, EPA has designated a new class of vehicles, light duty trucks, that will have different emission standards (gm/mi) than passenger cars (light duty vehicles). Basically, the light duty truck class is formulated to include all trucks that are used similarly to light duty vehicles.

Table 2-23. Percent (National Averages) of In-Use Trucks in Various Weight Classes[a]

| GVW[b] Class | GVW Class as % of all Trucks[c] | Trucks with GVW >6000 lbs (%) |
|---|---|---|
| <6000 | 63.0 | - |
| 6-10,000 | 18.5 | 50.0 |
| 10-14,000 | 0.3[d] | 0.8 |
| 14-16,000 | 1.3 | 3.5 |
| 16-19,000 | 4.5 | 12.2 |
| 19-26,000 | 6.5 | 17.6 |
| 26-33,000 | 2.0 | 5.4 |
| >33,000 | 3.9 | 10.5 |

[a] 1972 and 1973 Motor Truck Facts (Ref. 2-18)

[b] GVW = gross vehicle weight rating, lb

[c] There were approximately 20 million trucks registered in 1973.

[d] As of 1970, before the recreational vehicles sales showed a marked increase in this weight class.

summarized in Table 2-24. The engine must satisfy the cited standards after a prescribed durability test of 1000 to 1500 hr.

The wide variation in the types, weights, and uses of heavy duty vehicles as contrasted with the corresponding much smaller variation for light duty vehicles, plus the basic difference in the emission regulation approach taken by EPA for the two vehicle classes, makes it advisable to treat the I/M of heavy duty (GVW > 6000 lb) and light duty vehicles separately. Various aspects of vehicle emissions, maintenance, and alternative I/M approaches for heavy duty vehicles are considered in the next subsections.

Table 2-24. Federal Emission Standards for Heavy Duty Engines

| | |
|---|---|
| Gasoline-Fueled Engines[a]<br>1970-73<br>HC - 275 ppm $C_6$<br>CO - 1.5% (volume) | 1974<br>HC + $NO_x$ - 16 gm/bhp-hr<br>CO - 40 gm/bhp-hr |
| Diesel Engines[b]<br>1973<br>Smoke:<br>40% opacity - acceleration mode<br>20% opacity - lugging mode | 1974<br>HC + $NO_x$ - 16 gm/bhp-hr<br>CO - 40 gm/bhp-hr<br>Smoke:<br>20% opacity - acceleration mode<br>15% opacity - lugging mode<br>50% opacity - peaks |

[a] Nine-mode (2000 rpm, range of manifold vacuum) (Ref. 2-19)

[b] Thirteen-mode (intermediate and rated rpm, range of loads) (Ref. 2-20)

### 2.8.2 Heavy Duty Vehicle Emissions

There have been several recent studies of exhaust emissions from heavy duty gasoline-fueled trucks using both chassis dynamometer driving cycles and road routes (Refs. 2-21 and 2-22). Those studies indicate that truck emissions increase significantly with vehicle weight (curb-weight plus payload) and that even in the 4000 to 6000 lb inertia weight range vehicles (1970-1973) equipped with engines certified using heavy duty test procedures and emission standards seem to have emission levels much above those for light duty vehicles at the same inertia weight. This is illustrated in Figure 2-10, which shows the HC, CO, $NO_x$ emissions (gm/mi) for medium duty vehicles tested using the 1975 CVS-CH FTP at EPA and the Southwest Research Institute (SWRI) (Ref. 2-21).

Few measurements of exhaust emissions from heavy duty vehicles equipped with diesel engines have been made as yet. Predictions of emissions from diesel trucks have been made, however, in Ref. 2-23 based on diesel engine emission measurements (Ref. 2-24) (gm/bhp-hr at various engine loads and rpm) and calculated engine load factors in urban driving. Those predicted diesel emissions indicate that diesel HC and CO emissions are much lower than those for gasoline engines and that the $NO_x$ emissions from a diesel engine can be either lower or higher depending on the type of fuel injection used (prechamber or direct injection). Because diesel HC and CO emissions are much lower than for a gasoline engine, the emission problems usually associated with diesel engines are those of smoke and odor.

### 2.8.3 Mobile Source Emission Impact of Heavy Duty Vehicles

The contribution of heavy duty vehicles to mobile source emissions has been studied in some detail in Ref. 2-25 for several AQCRs. The importance of truck emissions compared with those from light duty vehicles depends on the number of each class of vehicles in the AQCR and the miles traveled by each class. The mix of vehicles and the average miles traveled per day by each class can be quite different in the

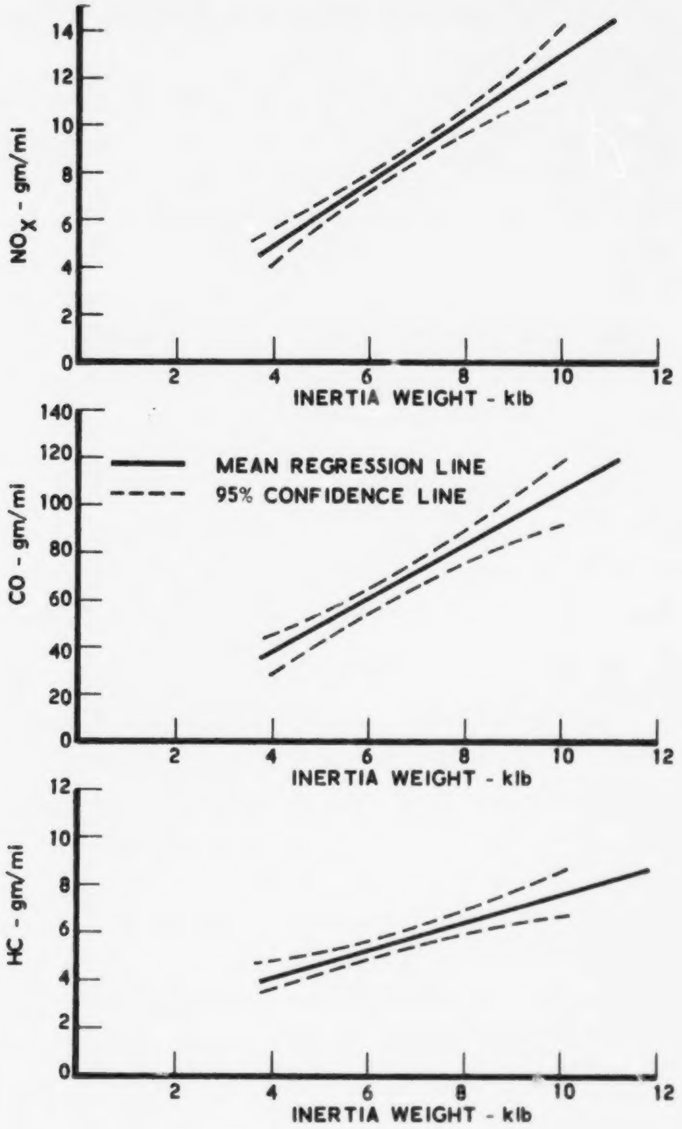

Figure 2-10. Variation of Emission Levels with Inertia Test Weight (1970 through 1973 trucks and motorhomes) (Ref. 2-23)

various regions. The projected percentage contributions of the light duty and heavy duty vehicle classes to the total mobile source emissions in some AQCRs for the period 1970 to 1990, assuming that only the presently promulgated emission standards[*] for light duty and heavy duty vehicles are implemented in that period, show that although at the present time the emissions from light duty vehicles are dominant this will gradually change in the next 20 years because the promulgated emission standards for light duty vehicles are much stricter than those for heavy duty vehicles. Unless the heavy duty engine emission standards are significantly tightened beyond those set forth for 1974 (Table 2-24), by 1990 the total exhaust emissions from trucks will be comparable to or greater than those from light duty vehicles (Ref. 2-25). Hence, even though the control of emissions from in-use trucks by I/M or retrofit strategies would not have nearly as large an impact on mobile source emissions at the present time as the same strategies applied to light duty vehicles, future projections indicate that this will not be the case in 10 years or even sooner in some AQCRs.

### 2.8.4 Surveillance Studies of Heavy Duty Engine Emissions

As noted previously, emission standards pertinent to heavy duty vehicles are not set for the vehicle itself, but rather for the engines to be used in such vehicles. Hence, emission surveillance studies of heavy duty vehicles involve emissions testing of engines after they have been in service in heavy duty vehicles for a specified time or mileage. Since removing the engine from the vehicle for testing on an engine dynamometer is both expensive and time consuming, studies have been done at SWRI to demonstrate that the engine can be emission tested while it is in the vehicle by the use of a chassis dynamometer (Ref. 2-26). The same set of steady-state engine test conditions (the nine-mode test procedure for gasoline engines) is used in the chassis dynamometer test as would be used if the engine were tested alone on an engine dynamometer. All of the engine emission surveillance results discussed in the following paragraphs were obtained using the chassis dynamometer test procedure.

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[*] For light duty vehicles, it was assumed that the interim 1975 and final 1976 HC and CO standards are implemented as scheduled. For heavy duty vehicles, it was assumed that the 1974 heavy duty standards are implemented and will remain unchanged until 1990.

The engine emission surveillance program reported in Ref. 2-26 involved the testing of about 150 1970-71 trucks[*] with GVW between 6000 and 34,000 lb. The emission tests were to be performed every 4 months over a period of about 2 years or 50,000 miles. Results are presently published for only the first 12 months of the program. At the start of the program, the engine in each truck was tuned to the manufacturer's specifications. Subsequent emission tests were conducted in the "as-received" condition, after which the basic ignition time and idle rpm were checked. If they were found to be outside tolerance (±3° for timing and ±100 rpm), they were adjusted and the engine emissions test repeated. The timing and rpm were reset at the as-received values before the truck was returned to the owner. It is of interest to compare the initial emissions characteristics of the trucks with those found after 12 months of service. This comparison is shown in Table 2-25. As would be expected, some deterioration of emissions was evident, with an increase in the average fleet HC emissions of 14 percent and an increase in CO emissions of 11 percent. The fleet average $NO_x$ emissions remained essentially unchanged (less than 1 percent) during the first 12 months of the surveillance program. Determination of whether the heavy duty engines continue to deteriorate with mileage or stabilize at the higher levels measured after the first year of the program must await publication of the data from the second year. At the end of the first year of the program, the CO emissions were above the Heavy Duty Engine Standard of 1.5 percent and HC emissions was very near the HC Standard of 275 ppm.

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[*] The initial mileage on most of the trucks was less than 10,000.

Table 2-25. Surveillance Study of Heavy Duty Engine Emissions Over 12 Months (Ref. 2-26)

| Months After Tune-Up[b] | No. of Trucks[c] | Emissions[a] | | |
|---|---|---|---|---|
| | | HC[d] (ppm) | CO[d] (%) | NO (ppm) |
| 0 | 152 | 239 | 1.61 | 1701 |
| 4 | 148 | 264 | 1.73 | 1873 |
| 8 | 148 | 261 | 1.89 | 1911 |
| 12 | 145 | 273 | 1.79 | 1703 |

[a] Nine-mode test procedure with vehicle on a chassis dynomometer.

[b] Vehicle given tune-up, and all components adjusted to manufacturer's specification.

[c] 1970-71 heavy duty vehicles - 6000 ≤ GVW ≤ 32,000 lb.

[d] 1970 Federal Heavy Duty Engine Emission Standards: HC - 275 ppm, CO - 1.5 percent.

As mentioned previously, the ignition timing and idle rpm of each truck was checked after it had been emissions tested in the as-received condition. At each testing period, about 20 percent of the trucks were found to be out of specifications, with early timing being the most frequent maladjustment. Unfortunately, idle CO or air/fuel ratio was not checked. The relatively high CO emissions of the fleet indicate that it is likely a number of the trucks needed a carburetor adjustment at idle or possibly at loaded conditions.

### 2.8.5 Voluntary Maintenance of Trucks and Other Heavy Duty Vehicles

The group of vehicles being considered in this section are very nonhomogeneous in size, shape, weight, use, and approach to maintenance. In discussing the maintenance of these vehicles, it is advantageous to consider the following categories: commercial and noncommercial, fleet and nonfleet operated, recreational, and gasoline-fueled and diesel engines. As indicated in Table 2-26, the approach to and level of maintenance can be expected to vary considerably from category to category (Ref. 2-27). In general, commercial vehicles are likely to be better maintained than noncommercial vehicles of the same type because minimizing lost time due to vehicle breakdowns and reducing fuel costs are important factors in conducting a profitable business. Owners of recreational vehicles would probably also maintain them better than the average passenger car because breakdowns away from home while traveling and/or vacationing would be both expensive and inconvenient. The best maintained vehicles are probably those operated as part of a fleet, for which the cost and inconvenience of scheduled and preventative maintenance is much less than if the same work were done at a private garage or dealer.

Detailed surveys of the maintenance practices and associated costs for the various truck and multipurpose vehicle categories are not presently available. However, limited inquiries to truck owners have indicated that most of the maintenance performed is directed toward safety checks* and lubrication. Engine tune-ups that are needed less frequently are seldom, if ever, done for any other reason than to improve vehicle performance and driveability. Except for reducing smoke from diesel engines, emission reduction is not a consideration. Even well-equipped, fleet-operated shops do not presently have exhaust gas analyzers. The recent marked increase in the concern of vehicle owners for fuel economy may tend to improve the situation relative to scheduled engine tune-ups, even for individual and small fleet owners. As in the case of the tune-up and repair of passenger cars, truck mechanics will need considerable instruction concerning emission-oriented tune-ups and the use of emission

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*Periodic safety inspection of commercial vehicles is required by law in some States. Random highway inspections by State Police or Highway Patrol officers are conducted in other States.

Table 2-26. Maintenance of Trucks and Other Heavy Duty Vehicles (Ref. 2-27)

| Vehicle Categories | Level of Maintenance | Place of Maintenance |
|---|---|---|
| Light duty trucks (GVW < 6000 lb)[a] | | |
| Noncommercial | Fair[b] | Independent garage/dealer |
| Commercial (nonfleet) | Fair/good[c] | Independent garage/dealer |
| Commercial (fleet) | Good[d] | Company facility |
| Gasoline-fueled heavy duty vehicle (GVW > 6000 lb) | | |
| Noncommercial | Fair | Independent garage/dealer |
| Commercial (nonfleet) | Fair/good | Independent garage/dealer |
| Commercial (fleet) | Good | Company facility |
| Recreational | Fair/good | Independent garage/dealer |
| Diesel heavy duty vehicle (GVW > 20,000 lb) | | |
| Commercial (nonfleet) | Good | Independent garage/dealer |
| Commercial (fleet) | Good | Company facility |

[a] All light duty trucks are gasoline fueled.

[b] Maintenance comparable to passenger cars.

[c] Somewhat better than for passenger cars.

[d] Scheduled and preventative maintenance.

measuring instruments in making repairs before the present rather extensive voluntary maintenance program can be expected to result in significant emission reductions from trucks.

Since trucks operated in fleets are on the average the best maintained, it is of interest to know how many and what type of trucks are operated in fleets and what maintenance schedules are followed. The larger the fleet, the more likely it is that scheduled maintenance (safety lube and engine tune-up) procedures are followed, and that the work is performed by experienced, qualified personnel. The minimum size fleet that is likely to have a shop and a qualified mechanic is one having about 10 vehicles. Data given in Ref. 2-18 indicate that about one-third of the in-use trucks are operated in fleets of that size or larger. The number, type, and use of vehicles in fleets of 10 or more vehicles are shown in Figure 2-11. It is common for the gasoline-fueled vehicles in such fleets to receive safety/mechanical checks and lubes every 4000 miles (or 3 months) and major engine tune-ups (replacement of spark plugs, points, etc.) every 12,000 miles (or 6 months). Engine maintenance of diesels is done much less frequently than for gasoline engines, with the period between major engine work being 50,000 miles in some cases. Including an emission inspection procedure as part of existing fleet maintenance programs would seem to be a logical step.

## 2.8.6 I/M Approaches for Trucks

### 2.8.6.1 General Considerations

In assessing the applicability of various I/M approaches to trucks, especially heavy duty trucks (GVW > 6000 lb), the following factors and special circumstances pertinent to the use and maintenance of such vehicles are important and should be considered:

a. The number and density of heavy duty vehicles in the region being considered.

b. The range of sizes, shapes, and weights included in the vehicle population.

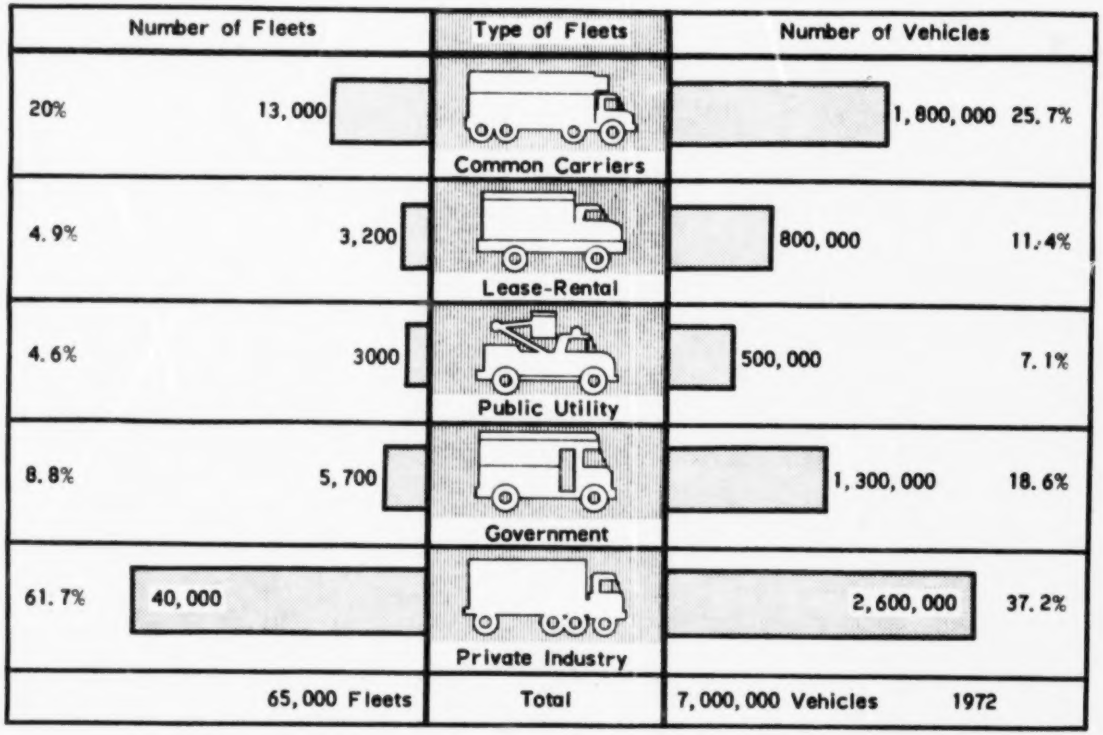

Figure 2-11. Vehicles in Fleets of 10 or more (Ref. 2-18)

c. The Federal emission standards and test procedures applicable to the in-use vehicles at the time they were produced.

d. A large part of the heavy duty population is operated for commercial purposes. Lost time and the cost of unscheduled maintenance are more significant to the owners of heavy duty vehicles than for most owners of light duty vehicles.

e. Fleet operation and maintenance are more common with heavy duty than with light duty vehicles.

f. Heavy duty chassis dynamometers are expensive and their availability is limited; therefore, experience with dynamometer testing of heavy duty vehicles is quite limited.

### 2.8.6.2 I/M Alternatives for Trucks

Various I/M approaches as they relate to light duty vehicles (primarily passenger cars) were discussed in Sections 2.1 through 2.7. The approaches considered fall into two broad categories: (1) an emission or engine parameter inspection, usually performed in State-owned and operated lanes, followed by the repair of rejected vehicles at an independent garage or dealer; and (2) mandatory periodic engine and emission control system maintenance, with the entire procedure being done at an independent garage or dealer. It was found that for light duty vehicles the cost effectiveness of the first approach (emission inspection/repair) was significantly better than that of the second (mandatory periodic maintenance) primarily because it is possible in the case of light duty vehicles to identify by a lane inspection those vehicles having high emissions that would benefit most from repair. For the reasons delineated in Section 2.8.6.1, the lane inspection approach does not seem practical for heavy duty vehicles. In addition, it is generally much more difficult to perform a meaningful emissions test on the larger vehicles in the heavy duty class that is both low in cost and of short duration. Hence, the circumstances surrounding truck operation indicate that mandatory periodic maintenance may be the I/M approach best suited for heavy duty vehicles. This approach would be equally applicable to individual truck and recreation vehicle owners and fleet operators. In addition, maintenance procedures could be specified for both gasoline-fueled and diesel engines. This flexibility in application is important because of the nonhomogeneity of the vehicles in the heavy duty class.

Since, as discussed in Section 2.8.5, many trucks receive scheduled safety checks and lubrication, and, in addition, a significant fraction receive periodic engine tune-ups, implementation of a mandatory periodic maintenance program for trucks directed toward engine emission reduction would not result in major changes in the maintenance schedules of some truck owners. The primary effects of a State specifying engine and emission control system maintenance procedures would be (1) that all truck owners would be subject to the same set of procedures and standards, and (2) that the mechanics doing the engine tune-up and repair work would necessarily become conscious of engine emission requirements. Enforcement of the mandatory engine maintenance regulations could be done by requiring evidence of compliance at the time of registration of the vehicle each year.

In contrast with the extensive studies of I/M related to light duty vehicles, there have not been any similar studies concerned with heavy duty vehicles. Since gasoline engines used in some heavy duty vehicles are essentially the same as those used in light duty vehicles, some of the information developed in the light duty vehicle studies may be applicable to these vehicles. However, since the power-to-weight ratio of heavy duty vehicles tends to be much less than that for light duty vehicles and as a result the engines in trucks operate at high loads a greater fraction of the time, the incremental effect on emissions (gm/mi) of most engine and emission control system malfunctions and maladjustments is likely to be greater than for light duty vehicles. Because of this, it is probable that idle emissions are an even less reliable indicator of road emissions for heavy duty than for light duty vehicles, and the use of chassis dynamometer testing becomes the only reasonably reliable approach to short emission testing of heavy duty vehicles. This is unfortunate, as a heavy duty dynamometer capable of simulating both the inertia and road horsepower of a heavy truck is expensive ($30,000 to $40,000) and not many are available. It is likely that a procedure for heavy duty vehicles analogous to the Key Mode test for light duty vehicles can be developed that would require a dynamometer with only power absorption capability. Possibly even a "beefed-up" light duty vehicle dynamometer could be developed for this I/M application. Emission inspection of heavy duty vehicles could be included as part of a mandatory maintenance program or be conducted at a stationary or mobile site as a random check on the emissions of such vehicles.

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# 3. RETROFIT OF EMISSION CONTROL SYSTEMS/ DEVICES FOR IN-USE VEHICLES

## 3.1 INTRODUCTION

Continuing advances in vehicle emission control technology suggest that retrofitting emission control devices or systems to in-use vehicles may be a useful approach to accelerate the reduction in vehicular emissions while these vehicles remain in use. The three main sources of vehicle emissions and thus possibilities for retrofit are the control of exhaust emissions, crankcase emissions, and evaporative emissions. A summary of the years in which emission controls were first used on new, light duty vehicles sold in the United States in order to comply with Federal and California emission standards is presented in Table 3-1. In general, retrofit approaches would be applied to vehicles not equipped at the factory with similar controls.

Thus, a retrofit approach is defined as the addition of a new item or system, or the modification or removal of an existing item of equipment beyond that of regular maintenance that is made to a motor vehicle after its initial manufacture for the purpose of reducing emissions.

### 3.1.1 Control of Exhaust Emissions

In order to control exhaust emissions, retrofit devices may either treat the exhaust gases after they leave the combustion chambers and enter into the exhaust system, or decrease pollutant formation in the engine by modifications to the induction, fuel, and ignition systems. Within these broad categories there are, as discussed in Section 3.2.1, a number of different approaches that can be pursued.

### 3.1.2 Control of Crankcase Emissions

Engine blowby results when the air/fuel mixture in the cylinder escapes past the piston rings during the compression and power strokes.

Table 3-1. Light Duty Vehicle Emission Control Requirements

| Control System | Model Year for Which Standards Were First Applicable | First Year Control Technique Introduced |
|---|---|---|
| Exhaust Emissions | | |
| HC and CO | 1968 (1966 Calif.) | |
| Engine modifications | | 1967 |
| Idle adjustments | | 1968 (1966 Calif.) |
| Timing modifications | | 1968 (1966 Calif.) |
| Air injection | | 1968 (1966 Calif.) |
| Catalyst | | 1975 |
| $NO_x$ | 1973 (1971 Calif.) | |
| Engine modifications | | 1973 (1971 Calif.) |
| Spark advance control | | 1973 (1971 Calif.) |
| EGR | | 1973 (1972 Calif.) |
| Crankcase Emissions | 1968 (1963 Calif.) | |
| PCV | | 1963 (1961 Calif.) |
| Evaporative Emissions | 1971 (1970 Calif.) | |
| Fuel tank and carburetor | | 1971 (1970 Calif.) |

The vapors enter the crankcase and subsequently escape to the atmosphere. Crankcase control systems provide a means of mixing air with the blowby gases in the crankcase and recirculating the mixture into the intake manifold, usually through a variable orifice control valve. The flow rate through the valve is controlled by intake manifold vacuum. Crankcase emissions control is discussed in Section 3.2.2.

### 3.1.3 Control of Evaporative Emissions

These systems control emissions from fuel that is evaporated from the fuel tank and carburetor. Gasoline tanks and carburetors are vented to the atmosphere on pre-1970 vehicles in California and on pre-1971 vehicles nationally. Losses from the tank result from diurnal temperature cycling, which causes expansion of the vapors in the tank. Losses at the carburetor occur almost entirely during the hot-soak period after shutting off the hot engine. Residual heat causes the temperature of the fuel bowl to rise to 150 to 200°F, which results in substantial boiling and vaporization of the fuel. Control of evaporative emissions is discussed in Section 3.2.3.

### 3.1.4 Criteria for Evaluation of Retrofit Emission Control Systems/Devices

The following criteria should be utilized to ascertain the feasibility of a retrofit emission control system:

a. The emissions reduction at low mileage and any change in reduction effectiveness (deterioration) at extended mileage.

b. The effects of the device on the driveability of the vehicle. This would include such factors as hesitation, stumble, surge, stall, or other factors affecting vehicle operational safety.

c. The effect on fuel consumption attributable to the retrofit system/device.

d. The cost of the device or system, including initial installation cost, annual maintenance cost, and any changes in fuel costs resulting from the use of the device. These data, in turn, can be used to determine the cost effectiveness of the device in terms of pounds of pollutants removed per dollar of cost.

e. The impact of the device, if any, on engine durability and reliability, such as might be caused by high coolant or exhaust gas temperatures or carburetor deposits.

f. The applicability of the device to the vehicle population in terms of its potential use on pre-1968, 1968-1971, etc. vehicles.

g. The ease or complexity of installation and maintenance. This evaluation can aid in determining the reasonableness of the cost estimates.

## 3.2 EVALUATION OF RETROFIT EMISSION CONTROL SYSTEM/DEVICES

### 3.2.1 Exhaust Emission Control

The following classes of exhaust emission control system/devices have been evaluated:

a. Engine Parametric Modifications. This type of retrofit is applicable to uncontrolled vehicles (pre-1968 nationwide, pre-1966 in California) and consists of carburetor, timing, and idle adjustments.

b. $NO_x$ Control. This retrofit system is especially directed toward those vehicles having only hydrocarbons (HC) and carbon monoxide (CO) controls (1968-1972 nationwide, 1966-1970 in California), but could be also used on uncontrolled vehicles. Two approaches are currently certified for use in California. One type uses exhaust gas recirculation (EGR) plus vacuum spark advance delay, while the other uses only vacuum spark advance disconnect.

c. Air Bleed. These devices are applicable to all vehicles, but are most effective on uncontrolled vehicles (see discussion, p. 3-13). Additional air is bled into the intake manifold at idle and part-throttle, thereby leaning the air/fuel ratio and reducing the HC and CO emissions, while potentially increasing $NO_x$ emissions.

d. Oxidation Catalytic Converter. This system utilizes an oxidation catalytic converter for the reduction of HC and CO. It could potentially be used on all pre-1975 vehicles capable of lead-free fuel operation. In general, the use of an oxidation catalyst requires an air pump to supply the oxygen to complete the oxidation of HC and CO.

e. Combination Systems. Numerous combinations of the above systems can be utilized to provide a particular combination of emission reductions. These include an oxidation catalyst and EGR, air bleed and vacuum spark advance delay, etc.

The Environmental Protection Agency (EPA) has provided initial estimates of reductions in exhaust emissions achievable through the installation of various types of retrofit devices on light duty vehicles (Table 3-2). These estimates were provided in Appendix N of 40 CFR 51* for

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*"Appendix N - Emission Reductions Achievable Through Inspection Maintenance and Retrofit of Light Duty Vehicles," Federal Register, Vol. 38, No. 110 (Friday, June 8, 1973).

Table 3-2. Estimated Emission Reductions for Retrofit of Light Duty Vehicles[a]

| Retrofit Option | Average Reduction Per Vehicle (%)[b] | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| **Precontrolled Vehicles** | | | |
| Lean idle air/fuel ratio adjustment and vacuum spark advance disconnect | 25 | 9 | 23 |
| Oxidizing catalytic converter and vacuum spark advance disconnect | 68 | 63 | 48 |
| Air bleed to intake manifold | 21 | 58 | 0 |
| Exhaust gas recirculation and vacuum spark advance disconnect | 12 | 31 | 48 |
| **Controlled Vehicles** | | | |
| Oxidizing catalytic converter | 50 | 50 | 0 |
| Exhaust gas recirculation | 0 | 0 | 40 |
| Oxidizing catalytic converter and exhaust gas recirculation | 50 | 50 | 40 |
| Air bleed to intake manifold[c] | 25 | 40 | 0 |

[a] Appendix N of 40 CFR 51 (Federal Register, Vol. 38, No. 110 (Friday, June 8, 1973)

[b] Reductions are to be applied to a maintained vehicle baseline (i.e., applied after emission reduction claimed for inspection/maintenance).

[c] Addendum to Appendix N of 40 CFR 51 (Federal Register, Vol. 38, No. 110 (Friday, June 8, 1973).

transportation control measure planning purposes. The data and discussions presented in the following sections are supplementary to that of Appendix N and are a summarization of currently available information related to the emission reduction performance and cost aspects of specific light duty vehicle retrofit approaches that have been or are currently being considered.

### 3.2.1.1 Engine Parametric Modifications

Two engine parametric modifications generally employed by the vehicle manufacturers in meeting Federal and California exhaust emissions standards have been the leaning of air/fuel ratios and the modification of ignition (spark) timing. Therefore, the modification of these parameters in precontrolled (pre-1968) vehicles can be used to reduce exhaust emissions also. Because 1968 and newer vehicles have utilized these modifications to some extent to meet Federal emissions standards, this retrofit technique can only be considered to be generally applicable to precontrolled vehicles.

#### 3.2.1.1.1 Description

Basically, this retrofit approach consists of three adjustments, i.e., increased idle speed to reduce HC on deceleration, a leaner idle mixture (14:1) to reduce HC and CO at idle, and vacuum spark advance disconnect and/or delay (VSAD). Engine overheating protection can be provided by a thermostatic vacuum switch that restores the normal spark advance if high coolant temperatures occur. The retrofit device referred to in the remainder of this section is this temperature sensing device.

#### 3.2.1.1.2 Emission Reductions

Emission tests have been conducted (Ref. 3-1) on a group of 1962-1967 vehicles using the 1972 CVS cold start test procedure in four different configurations. The first was the "as-received" or baseline configuration. The vehicles were then tested again after installation of the retrofit device. Following this, the vehicles were tuned, the retrofit device detached, and the "tuned" configuration tested. The final test was made with the retrofit device reinstalled and tested in combination with the tuned configuration.

The tune-up procedure consisted of the replacement of spark plugs, spark plug wires, distributor rotor, distributor cap, ignition points, condenser, and air filter element. As a part of the major tune-up, the idle mixture setting was set to give the best manifold vacuum at idle. All other tune-up settings were as specified by the vehicle manufacturer.

The relative effectiveness of the various procedures for reducing emissions is presented in Tables 3-3 and 3-4. As one would expect, the tuned plus retrofit configuration showed the greatest overall emission reduction.

Table 3-3. Emission Reduction from As-Received Baseline (Ref. 3-1)

| Emission | Emission Reduction (%) | | |
|---|---|---|---|
| | Retrofit Alone | Tune-Up | Tuned with Retrofit |
| HC-mean<br>95% confidence | 26<br>24 to 29 | 15<br>11 to 18 | 34<br>33 to 38 |
| CO-mean<br>95% confidence | 16<br>14 to 17 | 11<br>9 to 13 | 18<br>17 to 20 |
| NO-mean<br>95% confidence | 22<br>15 to 30 | -4 inc.<br>-18 to 10 | 20<br>13 to 27 |
| No. of vehicles in test sample | 110 | 85 | 110 |

Table 3-4. Emission Reduction from Tuned Baseline (Ref. 3-1)

| Emission | Emission Reduction Due To Retrofit (%) |
|---|---|
| HC-mean<br>95% confidence | 25<br>22 to 28 |
| CO-mean<br>95% confidence | 9<br>6 to 11 |
| $NO_x$-mean<br>95% confidence | 23<br>15 to 29 |
| No. of vehicles in test sample | 85 |

Durability tests conducted on this system to 25,000 miles indicated essentially no deterioration in emission reduction effectiveness for HC and nitrogen oxides ($NO_x$). A deterioration in CO reduction was noted and was attributable to an increase in idle enrichment, thus pointing up the need for annual maintenance to insure that the installed idle speed and mixture ratio are maintained.

### 3.2.1.1.3 Fuel Economy

Fuel consumption penalties associated with these devices have been reported to range from 2 to 6 percent, largely due to the ignition timing modifications.

### 3.2.1.1.4 Installed Cost

Kits containing parts needed for this retrofit have been marketed for approximately $10. The labor cost for installation is also about $10, bringing the total initial cost to the consumer to about $20.

### 3.2.1.1.5 Safety

There are no known adverse safety effects associated with this retrofit system.

### 3.2.1.1.6 Driveability

No serious driveability problems are associated with this retrofit system.

### 3.2.1.1.7 Reliability

The hardware used in these devices is not expected to present any reliability or durability problems, as it is similar to hardware used on production vehicles.

### 3.2.1.1.8 Maintenance

Annual maintenance is essential with this system, since the basic effectiveness in reducing emissions is contingent upon maintaining the as-installed idle speed, timing, and idle mixture. Annual maintenance costs associated with the carburetor adjustment and timing check are expected to be about $5 per year.

### 3.2.1.1.9 Applicability to Vehicle Population

This system is applicable to all pre-1968 domestic cars on a nationwide basis with the exception of those few not utilizing a centrifugal advance mechanism and similarly most pre-1966 cars in California. This amounts to approximately 40 percent of the U.S. passenger cars in operation, based on model year distribution data for 1973 (Ref. 3-2).

### 3.2.1.2 $NO_x$ Control

Historically, the introduction of emission controls to reduce HC and CO (1966 in California, 1968 nationally) resulted in a significant increase in $NO_x$ emissions. The development of retrofit devices to reduce the $NO_x$ emissions has been directed, therefore, primarily toward application to those vehicles currently having only HC and CO emission controls. This includes those cars sold in California from 1966-1970 and those sold nationally from 1968-1972, inclusive.

### 3.2.1.2.1 Description

Retrofit devices designed to reduce emissions of $NO_x$ are generally of two types. One relies entirely on spark timing retard and accomplishes this through VSAD or electronic modulation of the timing. Additional adjustments may be required at the time of installation of the device. These might include idle mixture adjustment to 1.5 to 2 percent CO and retard of the basic timing. This type of device may also incorporate provisions for overtemperature protection in the form of either an overspeed switch that restores full vacuum advance above a preset vehicle speed or a temperature sensing device that restores vacuum advance when the engine coolant reaches a certain temperature.

The other type of $NO_x$ emission reduction device utilizes a combination of EGR and VSAD. The EGR is accomplished by metering a quantity of exhaust gas from a connection to the engine exhaust system through a control valve to a T-connection with the positive crankcase ventilation (PCV) line leading to the intake manifold. The control valves differ substantially, but, in general, are responsive to a vacuum signal that controls valve operation. A vacuum delay element is used to provide varying degrees of spark retard under different operating conditions but allows full advance during cruise conditions to minimize fuel economy penalties. Since this type of device employs a delay rather than full vacuum disconnect (VSAD), overtemperature protection is not required. No change is required from the basic idle rpm or timing, but adjustment of mixture ratio to best lean idle is necessary in some cases.

### 3.2.1.2.2 Emission Reductions

Emission reductions from the $NO_x$ control devices are based primarily on emission measurements taken in support of manufacturers' applications for certification of the devices in the State of California (Ref. 3-3). The test data are based on the averages of 16 to 24 car fleets tested using the hot start 1972 CVS test procedure. Baseline vehicles were adjusted to manufacturers' specifications.

Average emission reductions at zero miles resulting from the installation of the VSAD type devices were 26 percent HC, 4 percent CO, and 45 percent $NO_x$. The average emission reductions for the EGR plus VSAD were 12 percent HC, 20 percent CO, and 53 percent $NO_x$.

It should be pointed out that these devices were designed primarily to reduce $NO_x$*. As a result, the extent of $NO_x$ reduction is fairly consistent among the various devices, but a wide variation exists in their effectiveness in reducing HC and CO. For example, average emission reduction variation ranges for the EGR type devices were: HC from 4 to 15 percent, CO from 16 to 43 percent, and $NO_x$ from 47 to 54 percent. Similar variations for the VSAD type device were: HC from 22 to 31 percent, CO from -3 (an increase) to 9 percent, and $NO_x$ from 42 to 50 percent (Ref. 3-3).

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*The California retrofit program for 1966-1970 vehicles was directed toward reducing $NO_x$ emissions by at least 40 percent without increasing HC and CO emissions.

Only limited data are available on the emission reduction effectiveness of these devices at extended mileage. The EGR type device has been operated to 12,000 miles with no significant change in $NO_x$ reduction. No extended mileage data is available on the VSAD only devices.

### 3.2.1.2.3 Fuel Economy

Fuel economy changes associated with the $NO_x$ retrofit devices have exhibited a wide variation on a car-to-car basis. Representative average values have been reported (Ref. 3-4) to range from a 3 to 7 percent penalty for the EGR type devices to a 6 to 10 percent penalty for the VSAD type devices, although actual fuel economy improvements were measured on a few individual vehicles.

### 3.2.1.2.4 Installed Cost

Both types of $NO_x$ devices are required by law in California to have an installed cost of not more than $35. It is assumed that the devices would be available on a nationwide basis at a similar cost.

### 3.2.1.2.5 Safety

There are no apparent safety hazards associated with these devices.

### 3.2.1.2.6 Driveability

No significant driveability problems were reported for the EGR type devices. Minor deterioration was reported for some VSAD devices, but driveability was considered acceptable.

### 3.2.1.2.7 Reliability

Both types of $NO_x$ devices are expected to have an estimated useful life of at least 50,000 miles, although actual durability tests have not been conducted.

### 3.2.1.2.8 Maintenance

The systems employing EGR are potentially susceptible to deposit formation in the EGR system and require annual maintenance of the EGR valve. The VSAD systems are susceptible to maladjustment of the basic timing settings and should also undergo annual maintenance. The VSAD systems have been shown (Ref. 3-4) to cause an increase in exhaust gas temperature (200 to 250°F at 60 mph), and a small percentage of the cars (approximately 5 percent) experienced coolant overheating under severe conditions. In this regard, it is of interest to note that a study has recently been completed by the California Department of Transportation (Ref. 3-5) in which the vacuum spark advance was disconnected on approximately 200 vehicles in normal motor pool use. No other modifications were made to these vehicles, which were in operation for approximately 11 months. Results indicated that there was no serious impairment of vehicle driveability nor could any adverse effects on needed engine maintenance be attributed to VSAD. Caution should be exercised in interpreting the results of this test program, however, since the effects of prolonged use at highway speeds and loads were not fully investigated.

Annual device-related maintenance cost for the $NO_x$ devices has also been set by statute in California at not more than $15. Actual costs are not expected to exceed this.

### 3.2.1.2.9 Applicability to Vehicle Population

The $NO_x$ retrofit devices have been specifically designed to be used on that portion of the vehicle population that has some degree of HC and CO control but no $NO_x$ control. Specifically, this means the 1966-1970 vehicles in California and the 1968-1972 vehicles nationally. There is no reason, however, why these $NO_x$ retrofit systems could not be used on precontrolled cars as well.

### 3.2.1.3 Air Bleed Devices

The HC and CO emissions can be reduced by leaning the air/fuel ratio at part-throttle conditions and during deceleration by introducing additional air into the intake manifold. This technique is applicable to some degree to all light duty vehicles; however, because of the increasingly lean air/fuel ratios on later model controlled vehicles, this retrofit technique can be expected to become less effective and in some cases may lead to lean misfire effects on later model vehicles.

### 3.2.1.3.1 Description

Retrofit devices of this type operate on the principal of bleeding air into the intake manifold in response to the manifold vacuum (difference between intake manifold and atmospheric pressures) to increase the air/fuel ratio. The additional air provides more complete oxidation of the CO and, to a lesser extent, HC during the combustion process. $NO_x$ emissions tend to increase unless other controls are used in conjunction with the air bleed devices. Adjustment of the idle mixture ratio at the time of installation is required for some, but not all, devices.

### 3.2.1.3.2 Emission Reductions

The emission reduction effectiveness of the air bleed devices has been evaluated for both uncontrolled vehicles (pre-1966 in California, pre-1968 nationally) and controlled vehicles (1968-1971). As expected, the controlled vehicles, which operate at a leaner air/fuel ratio than the uncontrolled vehicles, show a somewhat lesser reduction in CO.

Typical emission reductions that might be expected with the air bleed devices are 20 percent HC, 60 percent CO, and -5 percent $NO_x$ (increase) when installed on precontrolled vehicles and 20 percent HC, 50 percent CO, and a neglible change in $NO_x$ when installed on controlled (1968-1971) vehicles.

Note: It should be pointed out that extensive and consistent test data are not available on these devices; therefore, a reliable statistical evaluation of their emission reduction capability is not possible.

### 3.2.1.3.3 Fuel Economy

As was the case for emission reductions using air bleed devices, a large variation (-4 to +13 percent) in their effect on fuel economy has also been reported. A representative value for the pre-1968 vehicles is approximately a 4 percent savings. It would be expected that the controlled vehicles (1968-1971) would show a lesser improvement in fuel economy since the baseline vehicles are operating at a leaner air/fuel ratio than the uncontrolled vehicles. However, this is not substantiated by the limited available data, and the 4 percent fuel savings has been assumed for both groups of vehicles.

### 3.2.1.3.4 Installed Costs

The installed cost of the air bleed devices ranges from $20 to $60.

### 3.2.1.3.5 Safety

There are no apparent safety hazards associated with these devices unless severe lean misfire is encountered.

### 3.2.1.3.6 Driveability

No significant driveability problems were reported for the air bleed type devices, although some increase in acceleration times (approximately 10 percent) was reported for one of the devices (Ref. 3-6). Theoretically, of course, these devices would be characterized by lean operation tendencies, e.g., surge and hesitation. It should also be pointed out that the installation of an air bleed device on any vehicles already operating near the lean limit of combustion could result in misfire and possible severe adverse effects on driveability (and safety) of those vehicles.

### 3.2.1.3.7 Reliability

No specific reliability problems are anticipated for the air bleed devices.

### 3.2.1.3.8 Maintenance

Annual maintenance on the air bleed devices is not expected to require more than changing the filter (if used by the device) and checking the air/fuel ratio. Maintenance costs should not exceed $5 per year.

### 3.2.1.3.9 Applicability to Vehicle Population

The use of this device is applicable to both the uncontrolled (pre-1968) and the 1968-1971 vehicles, although the percent reduction in emission levels with 1968-1971 vehicles will be considerably lower than the uncontrolled vehicles. Its applicability to the 1972-1974 model vehicles is slight and therefore not recommended for application, since many of these cars are already operating at the lean limit of combustion and the use of the device would result in misfire and adverse driveability.

### 3.2.1.4 Oxidation Catalytic Converters

Oxidation catalysts as a retrofit device provide a means of achieving reduction of both HC and CO emissions, with little or no effect on $NO_x$ emissions. Tests (Refs. 3-7 through 3-9) of retrofit catalytic converters have been conducted in recent years. The most extensive test program to date is one currently being conducted by the California Air Resources Board involving a total to 100 vehicles (model year 1966 to 1972). These vehicles are used by State employees for transportation required in the conduct of State business and are tested every 4 months until each vehicle has been in State service for 2 years.

### 3.2.1.4.1 California Test Program

### 3.2.1.4.1.1 Description

The catalytic converter used in the California test contains approximately 170 grams of pellet catalyst (volume 33 cu. in.), with a loading of approximately 1 percent or 1.7 grams of platinum per converter. One converter is used on a six-cylinder engine and two on a V-8. The units are mounted in the engine compartment just below the exhaust manifold.

The 100 car test fleet was divided into groups A, B, and C as described below:

a. Group A. Consists of 11 vehicles with factory installed air pumps.

b. Group B. Consists of 29 vehicles without air pumps. For this group, effective catalytic conversion is dependent on adjusting the air/fuel ratio to a lean setting to provide the excess air for conversion.

c. Group C. Consists of 60 vehicles to which air pumps were added to provide the extra air needed for conversion. This group is considered to be the most likely candidate for a retrofit system.

#### 3.2.1.4.1.2 Emission Reduction

The reported test results of November 1973 on the California fleet are given in Table 3-5. Values shown are the average value for the number of vehicles tested at each 4-month interval using the cold start 1972 CVS test procedure. The program is scheduled to continue until all vehicles have been in service for 24 months. The Group A vehicles with factory-installed air pumps experienced the largest emissions reduction, which seemingly showed a stabilized reduction in HC and CO of 60 to 65 percent after 12 months and an average of 10,000 miles. The Group B vehicles, without air pumps, exhibited relatively low emission reduction potential early in the program when tested using a cold start and were phased out of the program. The Group C vehicles with retrofitted air pumps have shown HC and CO reductions of 65 to 70 percent at zero miles, but the reductions deteriorated to about 35 percent after 12 months and an average of 12,600 miles.

It will be noted from Table 3-5 that both the A and C groups of vehicles experienced a substantial deterioration in emission reduction during the first 4 months. As noted previously, the Group A vehicles (factory air pump) then remained fairly constant at 60 to 65 percent reduction in HC and CO, while the Group C vehicles (retrofit air pump) exhibited an additional deterioration in the 8 to 12 month period.

Table 3-5. Emission Test Results, 1972 CVS Cold Start California Fleet (Ref. 3-7)

| Group | No. of Vehicles[a] | HC | | CO | | Average Miles |
|---|---|---|---|---|---|---|
| | | gm/mi | Reduction (%) | gm/mi | Reduction (%)[b] | |
| A (factory air pump) | | | | | | |
| Baseline | 11 | 3.73 | | 44.64 | | |
| 0 Months | 11 | 0.69 | 81.5 | 4.95 | 88.9 | |
| 4 Months | 11 | 1.32 | 64.6 | 17.01 | 61.9 | |
| 8 Months | 10 | 1.31 | 64.9 | 17.30 | 61.2 | |
| 12 Months | 6 | 1.47 | 60.6 | 16.04 | 64.1 | 10,000 |
| C (retrofit air pump) | | | | | | |
| Baseline | 60 | 3.52 | | 42.23 | | |
| 0 Months | 60 | 1.09 | 69.0 | 14.39 | 65.9 | |
| 4 Months | 57 | 1.77 | 49.7 | 23.16 | 45.2 | |
| 8 Months | 32 | 1.86 | 47.2 | 22.21 | 47.4 | |
| 12 Months | 9 | 2.28 | 35.2 | 27.39 | 35.1 | 12,600 |
| B (no air pump)[c] | | | | | | |
| Baseline | 29 | 2.89 | | 30.9 | | |
| 0 Months | 29 | 1.43 | 50.5 | 21.0 | 32.0 | |
| 4 Months | 24 | 2.10 | 27.3 | 35.8 | -15.8 | |

[a] Number of vehicles shown tested after the various time periods varies due to differences in when the retrofitted vehicles were placed in service and the status of the test program at the time referenced reports were written. In addition, there have been seven catalyst failures (burn-out or mechanical problems) in Group C.

[b] Negative value indicates an increase in emissions.

[c] This group was phased out of the program.

Investigation indicated that the baseline emissions were increasing as the 1966-1972 test vehicles accumulated additional mileage. As reported in Ref. 3-10, 39 vehicles in Group C (with retrofit air pumps) have received rebaseline tests after 16 months. Results of these tests, shown in Table 3-6, indicate that these vehicles are maintaining HC and CO reductions in the 40 to 45 percent range.

Table 3-6. Rebaselined Emissions, California Fleet (June 1974)

| | No. of Cars | Exhaust Emissions (gm/mi) | | | Average Mileage |
|---|---|---|---|---|---|
| | | HC | CO | $NO_x$ | |
| Group C | 39 | 1.86 | 29.7 | -- | 17,360 |
| Rebaseline[a] | 39 | 3.29 | 54.2 | -- | 17,380 |
| Reduction | - | 43% | 45% | | |

[a] Without converters

In order for the oxidation catalytic converter to be an attractive retrofit device, it is necessary that the deterioration it experiences in use be quite low. While sufficient data are available to conclude with some confidence that the initial (zero miles) emission reduction on retrofitted vehicles is high (70 to 90 percent) for both HC and CO, there is not sufficient data at present to conclude that the needed low deterioration can be achieved. In light of the promising deterioration results over 12,000 miles in the California tests for the vehicles with factory-installed air pumps and the improving deterioration-resistant characteristics of catalysts on prototype 1975-76 vehicles (Refs. 3-11 through 3-13), there is certainly a reasonable likelihood that the low deterioration requirement for retrofit converters can be met in the not too distant future.

It is certainly reasonable to assume that continued improvements in the deterioration resistance of catalysts for new vehicles in the years ahead will be reflected in potentially lower deterioration rates for retrofitted converters. However, these improvements should not be accepted per se for retrofit devices without extensive testing because the configuration, location, and engine system in which the original equipment and retrofit converters are used are quite different. For example, currently the retrofit converters are smaller in volume, have a higher loading of active metal, and are located closer to the engine than converters used in new vehicles. In addition, the retrofit converters will not benefit from the improved choke, ignition, and carburetor systems used in 1975-76 vehicles. Further, it is difficult to provide comparable over-heat protection for the retrofit converters. In summary, it can be said that solving the catalyst deterioration problem for new vehicles does not necessarily mean the problem is solved for the retrofit of catalysts to in-use vehicles.

### 3.2.1.4.1.3 Fuel Economy

Results of the California tests indicate only that there have been no reports of loss in fuel economy among the fleet vehicles. No quantitative data on fuel consumption were reported. In this regard, however, it should be pointed out that primarily fuel economy effects will depend largely on the nature of parametric adjustments (timing, etc.), if any, made during the installation of the retrofit system.

### 3.2.1.4.1.4 Installed Cost

The installed cost of the catalytic converter retrofit system has been estimated from the manufacturers and other cost data presented in Reference 3-6. For a V-8, these costs are:

| | | |
|---|---|---|
| Converters (2) | $50.00 | |
| Converter installation | 20.00 | |
| Converter Total | | $70.00 |

| | | |
|---|---|---|
| Air pump | $45.00 | |
| Air pump installation | 40.00 | |
| Air Pump Total | | $ 85.00 |
| Total Installed Cost | | $155.00 |

From the above, it can be seen that the air pump represents a significant portion of the installed cost (and cost effectiveness of the system). Research to develop alternatives for the currently necessary use of an air pump is continuing.

### 3.2.1.4.1.5 Driveability

No adverse driveability problems, i.e., loss of performance, has been reported.

### 3.2.1.4.1.6 Maintenance

Average maintenance costs associated with the catalyst (with air pump) are not expected to exceed $15 per year. These costs would include an annual replacement of any loss due to shrinkage and a possible complete replacement of the catalyst (pellets only) every 25,000 miles. Replacement costs for the pelletized catalytic material are uncertain, but a cost of $7 per converter has been suggested by the manufacturer.

### 3.2.1.4.1.7 Applicability to Vehicle Population

The catalyst retrofit device would be applicable to those pre-1975 cars whose engines are capable (knock-free and without damage to valves) of operating on lead-free 91 RON fuel. To insure against the use of leaded fuel, consideration must be given to the retrofit of a fuel tank neck restriction similar to that planned for the 1975 model year vehicles that will be catalyst equipped and also require lead-free fuel.

### 3.2.1.5 Combinations of Retrofit Control Systems

Combinations of the systems discussed in the previous sections offer the potential to achieve larger combined reductions in HC, CO, and $NO_x$ for both uncontrolled (pre-1968) and controlled 1968-1971 vehicles than possible with the individual systems alone.

### 3.2.1.5.1 Air Bleed and $NO_x$ Control

One of the combination systems employs an air bleed device and either a vacuum delay valve for vacuum spark advance control or EGR.

#### 3.2.1.5.1.1 Emission Reduction

Although only limited emission reduction data are available for this combination system, projected emission reductions of 20 to 25 percent HC and 40 to 50 percent CO are consistent with available data. $NO_x$ reductions of 10 to 20 percent for the air bleed plus vacuum delay and 30 to 40 percent for the air bleed plus EGR are projected.

#### 3.2.1.5.1.2 Fuel Economy

Fuel economy for the combined system is expected to show an improvement over that for the $NO_x$ device alone because of the leaning effect of the air bleed device, which when used alone improves fuel economy by about 4 percent. Hence, the net effect of the two retrofitted devices together is estimated to be only a slight fuel penalty of 1 to 2 percent at most. Test data to confirm this estimate are not currently available.

#### 3.2.1.5.1.3 Installed Cost

The installed cost of the air bleed and vacuum delay devices has been quoted as approximately $25 (Ref. 3-14). The cost of the air bleed and EGR combination is estimated to be about $40 to $50.

#### 3.2.1.5.1.4 Applicability to Vehicle Population

This combined system could be used on most pre-1973 vehicles that did not have a factory-installed $NO_x$ control system.

### 3.2.1.5.2 Oxidation Catalyst and EGR

A second combination system that will be considered is the oxidation catalyst and EGR. This system also requires a means of adding additional air (oxygen) to the exhaust gases either by leaner carburetion or by the use of an air pump. Systems have been tested with and without air pumps and in addition the possibility of using an air bleed device is currently being studied.

### 3.2.1.5.2.1 Emission Reduction

The combined system of oxidation catalyst and EGR has not been tested using controlled light duty vehicles, but the initial emission reduction characteristics (Table 3-7) of such a system can be estimated using the characteristics of the separate systems given previously. These estimates are thought to be appropriate, since the catalyst and $NO_x$ control systems do not interact significantly.

Table 3-7. Oxidation Catalyst and EGR Systems

| Configuration | Emission Reductions[a] (%) | | | Fuel Economy Change (%) |
|---|---|---|---|---|
| | HC | CO | $NO_x$ | |
| With air pump | 70 | 65 | 53 | -3 |
| Without air pump | 50 | 32 | 53 | -3 |

[a] All emissions relative to 1972 CVS-C FTP.

The data in Table 3-7 are for low mileage tests. The effect of deterioration is likely to be important, but the rapidly changing catalyst technology and lack of fleet data for the new catalysts makes it impossible to assess retrofit catalyst deterioration in a meaningful manner at the present time.

### 3.2.1.5.2.2 Fuel Economy

The fuel penalty for this combined system was estimated to be 3 percent, which is slightly less than for the EGR system alone.

### 3.2.1.5.2.3 Installed Cost

The installed cost of this combined system can be determined by simply adding the costs of the individual systems because their installations are not interrelated. Hence, the installed cost would be $190, including an air pump, and $105 if the retrofitting of an air pump is not required for cars already equipped with one.

### 3.2.1.5.2.4 Applicability to the Vehicle Population

This [illegible] system would be most directly applicable to 1970-1972 vehicle [illegible] do not have $NO_x$ control emission systems and can operate on lead[illegible] (low octane) gasoline.

### 3.2.1.6 Retrofit Emission Control at High Altitude*

It must be emphasized that much of the discussion of the retrofit at high altitude is based on the following: data from three sources only, very limited sample sizes, hot start emissions tests, dissimilar vehicles, and on device proponent's emissions data and cost estimates. There remains considerable data to be gathered before the magnitude of the emission reduction by retrofit at altitude can be ascertained. It is strongly suggested that before any high altitude retrofit program be initiated, a comprehensive and thorough altitude retrofit evaluation be conducted on vehicles representing the local high altitude vehicle population. Consideration must be given also to the availability of devices optimized for high altitude retrofit, engineering development problems associated with specialized high altitude retrofit, and operation of a high altitude retrofit device at sea level. However, these data are the only data available and are presented to complete the retrofit scenario.

Differences in emission levels occur in gasoline-fueled vehicles when operated at high altitude. These changes are the result of fuel metering enrichment due to the atmospheric pressure (and density) variations with altitude. Since the air/fuel ratio is proportional to the square root of the air density, operation of a motor vehicle at an altitude of 5000 feet would theoretically result in a decrease in the air/fuel ratio of 7.2 percent. In the normal operating ranges, this is equivalent to a decrease of approximately one air/fuel unit. The effect of this, in general, can be seen in Figure 3-1, which shows typical emission levels as a function of the air/fuel ratio. The actual magnitude will vary, depending on the operating range of the vehicle.

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*High altitude means any elevation over 4,000 feet.

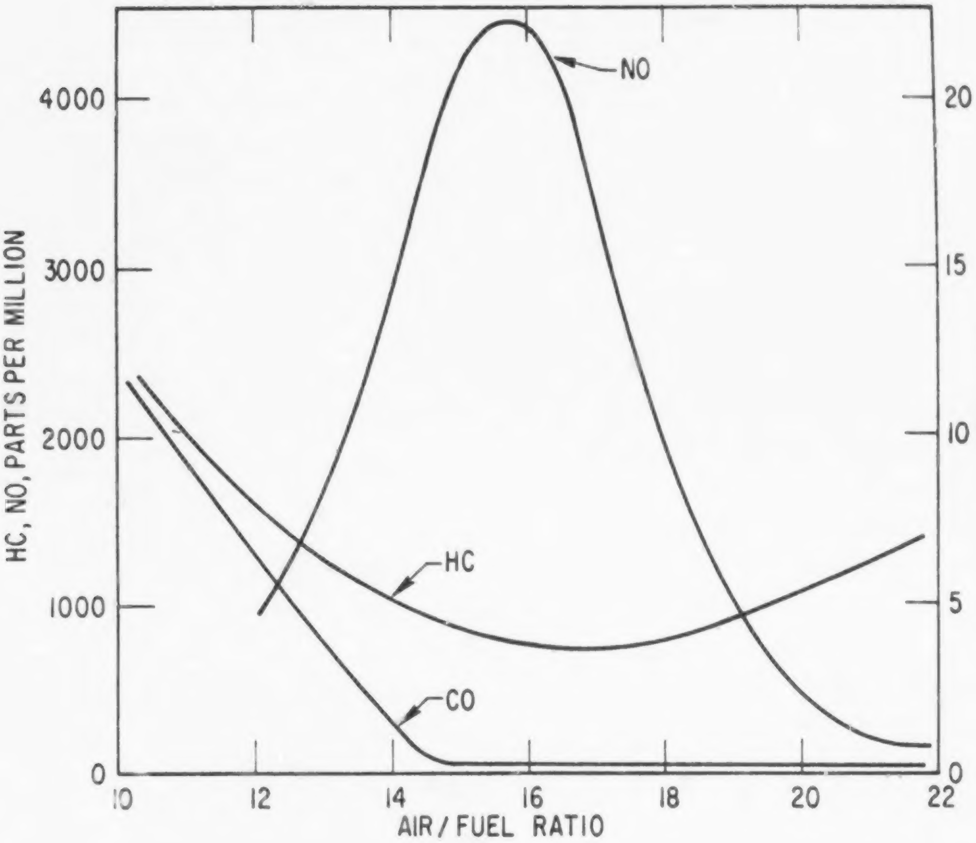

Figure 3-1. Typical Spark Ignition Engine Exhaust Emission vs Air/Fuel Ratio (Gasoline) (Ref. 3-15)

Typical changes in emission levels for vehicles operating at altitude are shown in Table 3-8. The changes are based on cold start 1975 results from CVS test results found in Denver, Colorado, (Ref. 3-16) and compared to the average from similar tests conducted in low altitude cities.

Table 3-8. Emission Changes at Altitude (Denver, Colorado)

| Model Year | % Change Due to Altitude | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| Pre-1968 | +16.7 | + 46.7 | -46.6 |
| 1968-1971 | +47.8 | + 71.1 | -45.7 |
| 1972-1974 | +81.5 | +121.1 | -37.9 |

It can be inferred from Table 3-8 that the retrofit of vehicles operating at altitude should be directed toward the reduction of CO and HC. Vehicle emission control programs for high altitude, including retrofit strategies, are discussed in Refs. 3-17 and 3-18.

Additional problems associated with vehicle operation at high altitude arise from the reduction in power due to the lower ambient air density. The power loss is proportional to the ambient density (Ref. 3-19), which means approximately a 14 percent reduction in power at 5,000 feet. To compensate for this, the vehicle must be operated at lower manifold vacuum and higher rpm than at sea level to obtain the same output power from the engine. The reduced power makes the effect of spark retard on engine operation most noticeable. Also, the lower manifold vacuum tends to reduce the amount of air bled into the intake manifold through any particular air bleed valve configuration.

### 3.2.1.6.1 Description

A number of control devices have been tested, either singly or in combination, in Denver, Colorado, to determine their effectiveness in reducing emissions at high altitude (Refs. 3-14, 3-17, 3-20). The systems tested include the following:

a. Air Bleed. This is the same device previously discussed in Section 3.2.1.3 (Device A).

b. Air Bleed and a Vacuum Delay Valve. This is the same system discussed in Section 3.2.1.5.

c. Exhaust Gas Recirculation (EGR). This is the same system discussed in Section 3.2.1.2 (Device A).

d. EGR and Enleanment. The EGR unit (Section 3.2.1.2, Device B) was used in combination with enleanment accomplished by installing an oversized PCV valve (4-10CFM).

e. EGR, Enleanment, and an Oxidation Catalyst with an Air Pump. The oxidation catalyst was the same type used in the California test fleet (Section 3.2.1.4).

f. Manufacturer High Altitude Kits. For use on post-1967 vehicles.

#### 3.2.1.6.2 Emission Reductions

Emission test results for each of the systems are presented in Table 3-9. It must be noted that most of the tests were conducted using a hot start 1972 CVS test procedure. Because of the small number of vehicles tested and the fact that a hot rather than cold start test procedure was used, these results must be considered only as indicative of potential emission reductions that may be achieved and not necessarily representative of a large vehicle population in actual use. There are, however, several trends in the data given in Table 3-9 that should be noted. First, and probably most important, it is apparent that for HC and CO emissions only the catalytic converter reduces the emissions (gm/mi) at high altitude to levels equal to or less than those experienced at sea level without retrofit devices. As indicated in Ref. 3-17, the emission reductions found using manufacturer-supplied high altitude kits were small, with only the Chrysler kit having a significant effect on HC and CO but with a large increase of $NO_x$ emissions. It would seem that by changing carburetor jets and altering centrifugal advance weights in the distributor to compensate for the effects of reduced ambient

Table 3-9. Retrofit Emission Control at High Altitude

| System | No. of Vehicles | Model Year | Test Procedure | Emission Reduction (%)[a] |  |  | Source of Data (Ref.) |
|---|---|---|---|---|---|---|---|
|  |  |  |  | HC | CO | $NO_x$ |  |
| a. Air bleed (Device A) | 1 | 1964 | Hot 72CVS | 52 | 34 | -36 | 3-14 |
| b. Air bleed and vacuum delay | 1 | 1972 | Hot 72CVS | 15 | 28 | 48 | 3-14 |
| c. EGR (Device A) | 1 | 1969 | Hot 72CVS | 25 | 36 | 45 | 3-20 |
|  | 1 | 1970 | Hot 72CVS | 15 | 41 | 28 |  |
| d. EGR (Device B) and enleanment | 5 | 1966-1969 | Hot 72CVS | 16 | 48 | 36 | 3-20 |
| e. EGR (Device B) | 1 | 1966[b] | Hot 72CVS | 75 | 92 | 30 | 3-20 |
| enleanment, and catalyst with air pump | 1 | 1969 | Hot 72CVS | 81 | 92 | 51 |  |
|  | 1 | 1966 | Hot 72CVS | 61 | 93 | 72 |  |
| f. Chrysler high altitude kit | 15 | 1968-1973 | Cold 75CVS | 26 | 54 | -84 | 3-17 |

[a] A negative value indicates an increase in emissions.

[b] This vehicle was not equipped with any enleanment device.

density and manifold vacuum, it would be possible to reduce baseline engine emisssions at high altitude to near sea-level values. This appears to be a logical first step in a retrofit program for reducing emissions from in-use vehicles at altitude.

Several conclusions can possibly be drawn from Table 3-9 regarding the effectiveness at high altitude of the various retrofit devices/systems. First, air bleed is somewhat less effective in reducing CO at altitude than it is at sea level (e.g., 34 percent CO reduction at altitude vs 50 to 60 percent at sea level). And, because the baseline operation of the engine at altitude is on the rich side of stoichiometric, leaning the mixture with an air bleed device results in a significant increase in $NO_x$ emissions. It is apparent that the air bleed devices designed for use at sea level do not permit the addition of sufficient air at altitude to even overcome the effects of reduced ambient density; however, an air bleed device could be designed to work at high altitude conditions. Second, the effects of both EGR and VSAD on $NO_x$ emissions are only slightly less at altitude than at sea level even though the baseline $NO_x$ emissions are lower at altitude. The effect of EGR on the HC emissions seems to be about the same at altitude as at sea level. Third, a retrofit catalyst with an air pump apparently functions well at altitude, which yields higher HC and CO emission reductions than at sea level. It is likely that because of limitations on possible engine modifications to reduce emissions at altitude the catalyst system will be somewhat more attractive at altitude than at sea level.

### 3.2.1.6.3 Fuel Economy

Fuel economy data were not available on the systems tested except for the three vehicles equipped with the catalyst. Those vehicles showed an average fuel penalty for the combined system (catalyst and EGR) of less than 2 percent.

### 3.2.1.6.4 Installed Cost

Installed cost of the various devices/systems tested are summarized below:

a. Air Bleed. The installed cost of this device has been estimated to be $20.

b. Air Bleed and Vacuum Delay. The installed cost of this combination is between $25 and $35, depending on the method of affecting the VSAD.

c. EGR (Device A). The cost of this device is $35.

d. EGR (Device B) and Enleanment. The cost of this combination is between $40 to $45, depending on the cost of the high flow rate PCV valve.

e. EGR (Device B), Enleanment, Catalyst, and Air Pump. The installed cost of this system would be about $195 on a V-8 requiring two catalyst units. The cost of catalysts and air pump alone are about $155.

f. Manufacturer's High Altitude Kits. The cost of these kits installed is given as $8 to $13 in Ref. 3-17.

### 3.2.1.7 Summary of Emission Reductions and Cost Effectiveness of Retrofit Exhaust Emission Control Systems

The emission reduction and cost effectiveness ($/lb of emission reduction) characteristics of each of the retrofit devices/systems considered are summarized in Tables 3-10, 3-11, and 3-12 for HC, CO, and $NO_x$, respectively. Each system is shown for the particular model years for which it is applicable. Incremental fuel costs over 50,000 miles for the model years of interest have been calculated using the fuel economy values given in Ref. 3-21 as the baseline (before retrofit) for the model years of interest and the fuel economy change factors (percent of increase or decrease) presented earlier in this section. The baseline fuel economy values were adjusted to reflect 1975 FTP results using the procedure of Ref. 3-21. The unit fuel cost was taken to be $0.50 per gallon, and any change from this value would require a re-evaluation of the total cost associated with a given device. Baseline emissions (without retrofit devices) were taken from Reference 3-16.

## Table 3-10. Cost Effectiveness Summary, Light Duty Vehicles HC Emission Reductions[a]

| System | Installed Cost ($) | 50,000-Mile Maint. Cost ($) | Fuel Penalty (%)[b] | Fuel Cost ($)[b] | HC Baseline Emissions (gm/mi) | HC % Reduction | HC Reduction (gm/mi) | HC Emission Reduction 50,000-Mile Cost ($/lb) | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Excl. Fuel | Incl. Fuel | |
| 1. Engine modifications | | | | | | | | | | |
| Pre-1968 | 20.00 | 25.00 | 4 | 74.00 | 8.9 | 25 | 2.2 | 0.18 | 0.49 | |
| 2. Air bleed | | | | | | | | | | |
| Pre-1968 | 20.00 | 25.00 | -4 | -74.00 | 8.9 | 20 | 1.8 | 0.23 | -- | |
| 1968-1971 | 20.00 | 25.00 | 4 | 73.00 | 4.8 | 15 | 0.7 | 0.57 | -- | |
| 3. $NO_x$ device-VSAD type | | | | | | | | | | |
| Pre-1968 | 35.00 | 25.00 | -- | -- | -- | -- | -- | -- | -- | Insufficient data on pre-1968 vehicles |
| 1968-1971 | 35.00 | 25.00 | 8 | 155.00 | 4.8 | 25 | 1.2 | 0.44 | 1.58 | |
| $NO_x$ device-EGR type | | | | | | | | | | |
| Pre-1968 | 35.00 | 25.00 | -- | -- | -- | -- | -- | -- | -- | |
| 1968-1971 | 35.00 | 25.00 | 5 | 98.00 | 4.8 | 12 | 0.6 | 0.95 | 2.49 | |
| 4. Oxidation catalyst | | | | | | | | | | (1) Emission reductions at zero miles. Deterioration of emission reduction with mileage not included. (2) Requires use of unleaded fuel. (3) Costs are for V-8 (6 cyl. approximately $50 less). |
| 1968-1971 | | | | | | | | | | |
| with air pump | 155.00 | 75.00 | 0 | 0 | 4.8 | 70 | 3.4 | 0.62 | 0.62 | |
| w/o air pump | 70.00 | 65.00 | 0 | 0 | 4.8 | 50 | 2.4 | 0.51 | 0.51 | |
| 1972-1974 | | | | | | | | | | |
| with air pump | 155.00 | 75.00 | 0 | 0 | 2.8 | 70 | 2.0 | 1.07 | 1.07 | |
| w/o air pump | 70.00 | 65.00 | 0 | 0 | 2.8 | 50 | 1.4 | 0.88 | 0.88 | |
| 5. Air bleed + vac delay | | | | | | | | | | |
| Pre-1968 | 25.00 | 25.00 | 0 | 0 | 8.9 | 25 | 2.2 | 0.20 | 0.20 | |
| 1968-1971 | 25.00 | 25.00 | 0 | 0 | 4.8 | 20 | 1.0 | 0.47 | 0.47 | |
| 6. Air bleed + EGR | | | | | | | | | | |
| Pre-1968 | 35.00 | 55.00 | 1 | 19.00 | 8.9 | 25 | 2.2 | 0.33 | 0.41 | |
| 1968-1971 | 35.00 | 55.00 | 1 | 20.00 | 4.8 | 20 | 1.0 | 0.76 | 0.94 | |
| 7. Catalyst + EGR | | | | | | | | | | (1) Emission reductions at zero miles. Deterioration of emission reduction with mileage not included. (2) Requires use of unleaded fuel. (3) Costs are for V-8 (6 cyl. approximately $10 less). |
| 1968-1971 | | | | | | | | | | |
| with air pump | 190.00 | 75.00 | 3 | 59.00 | 4.8 | 70 | 3.4 | 0.72 | 0.88 | |
| w/o air pump | 105.00 | 65.00 | 3 | 59.00 | 4.8 | 50 | 2.4 | 0.64 | 0.87 | |

[a] All emissions relative to 1975 CVS-C FTP.

[b] A negative value indicates a savings; fuel penalty values shown are approximate average values based on limited data with a sometimes wide car-to-car variation.

## Table 3-11. Cost Effectiveness Summary, Light Duty Vehicles CO Emission Reductions[a]

| System | Installed Cost ($) | 50,000-Mile Maint. Cost ($) | Fuel Penalty (%)[b] | Fuel Cost ($)[b] | CO Baseline Emissions (gm/mi) | CO % Reduction | CO Reduction (gm/mi) | CO Emission Reduction 50,000-Mile Cost ($/lb) | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Excl. Fuel | Incl. Fuel | |
| 1. Engine modifications | | | | | | | | | | |
| Pre-1968 | 20.00 | 25.00 | 4 | 74.00 | 94 | [illegible] | 8.5 | 0.05 | 0.13 | |
| 2. Air bleed | | | | | | | | | | |
| Pre-1968 | 20.00 | 25.00 | -4 | -74.00 | 94 | 60 | 56.4 | 0.007 | | |
| 1968-1971 | 20.00 | 25.00 | 4 | -79.00 | 61 | 50 | 30.5 | 0.01 | [illegible] | |
| 3. NO$_x$ device-VSAD type | | | | | | | | | | |
| Pre-1968 | 35.00 | 25.00 | -- | -- | -- | -- | -- | -- | -- | Insufficient data on pre-1968 vehicles |
| 1968-1971 | 35.00 | 25.00 | 8 | 157.00 | 61 | 4 | 2.4 | 0.22 | 0.18 | |
| NO$_x$ device-EGR type | | | | | | | | | | |
| Pre-1968 | 35.00 | 25.00 | -- | -- | -- | -- | -- | -- | -- | |
| 1968-1971 | 35.00 | 25.00 | 5 | 98.00 | 61 | 6 | 3.7 | 0.15 | 0.39 | |
| 4. Oxidation catalyst | | | | | | | | | | (1) Emission reductions at zero miles. Deterioration of emission reduction with mileage not included. (2) Requires use of unleaded fuel. (3) Costs are for V-8 (6 cyl. approximately $30.00 less). |
| 1968-1971 | | | | | | | | | | |
| with air pump | 155.00 | 75.00 | 0 | 0 | 61 | 65 | 39.7 | 0.05 | 0.05 | |
| w/o air pump | 70.00 | 65.00 | 0 | 0 | 61 | 32 | 19.5 | 0.06 | 0.06 | |
| 1972-1974 | | | | | | | | | | |
| with air pump | 155.00 | 75.00 | 0 | 0 | 30 | 65 | 19.5 | 0.11 | 0.11 | |
| w/o air pump | 70.00 | 65.00 | 0 | 0 | 30 | 32 | 9.6 | 0.13 | 0.13 | |
| 5. Air bleed + vac. delay | | | | | | | | | | |
| Pre-1968 | 25.00 | 25.00 | 0 | 0 | 94 | 55 | 51.7 | 0.009 | 0.009 | |
| 1968-1971 | 25.00 | 25.00 | 0 | 0 | 61 | 50 | 30.5 | 0.01 | 0.01 | |
| 6. Air bleed + EGR | | | | | | | | | | |
| Pre-1968 | 35.00 | 55.00 | 1 | 19.00 | 94 | 40 | 37.6 | 0.019 | 0.024 | |
| 1968-1971 | 35.00 | 55.00 | 1 | 20.00 | 61 | 40 | 24.4 | 0.03 | 0.037 | |
| 7. Catalyst + EGR | | | | | | | | | | (1) Emission reductions at zero miles. Deterioration of emission reduction with mileage not included. (2) Requires use of unleaded fuel. (3) Costs are for V-8 (6 cyl. approximately $30 less). |
| 1968-1971 | | | | | | | | | | |
| with air pump | 190.00 | 75.00 | 3 | 59.00 | 61 | 65 | 39.7 | 0.06 | 0.07 | |
| w/o air pump | 105.00 | 65.00 | 3 | 59.00 | 61 | 32 | 19.5 | 0.08 | 0.11 | |

[a] All emissions relative to 1975 CVS-C FTP.

[b] A negative value indicates a savings; fuel penalty values shown are approximate average values based on limited data with a sometimes wide car to car variation.

## Table 3-12. Cost Effectiveness Summary, Light Duty Vehicles $NO_x$ Emission Reductions[a]

| System | Installed Cost ($) | 50,000-Mile Maint. Cost ($) | Fuel Penalty (%)[b] | Fuel Cost ($)[b] | $NO_x$ Baseline Emissions (gm/mi) | $NO_x$ % Reduction | $NO_x$ Reduction (gm/mi) | $NO_x$ Emission Reduction 50,000-Mile Cost ($/lb) Excl. Fuel | Incl. Fuel | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 Engine modifications | | | | | | | | | | |
| Pre-1968 | 20.00 | 25.00 | 4 | 74.00 | 3.4 | 23 | 0.8 | 0.52 | 1.38 | |
| 2 Air bleed | | | | | | | | | | |
| Pre-1968 | 20.00 | 25.00 | -4 | -74.00 | 3.4 | 0 | 0 | -- | | |
| 1968-1971 | 20.00 | 25.00 | -4 | -74.00 | 4.8 | 0 | 0 | | | |
| 3 $NO_x$ device-VSAD type | | | | | | | | | | |
| Pre-1968 | 35.00 | 25.00 | -- | -- | -- | -- | -- | | -- | Insufficient data on pre-1968 vehicles |
| 1968-1971 | 35.00 | 25.00 | 8 | 157.00 | 4.8 | 45 | 2.2 | 0.25 | 0.91 | |
| $NO_x$ device-EGR type | | | | | | | | | | |
| Pre-1968 | 35.00 | 25.00 | | -- | -- | -- | -- | | | |
| 1968-1971 | 35.00 | 25.00 | 5 | 98.00 | 4.8 | 53 | 2.5 | 0.21 | 0.56 | |
| 4 Oxidation catalyst | | | | | | | | | | (1) Emission reductions at zero miles. Deterioration of emission reduction with mileage not included. (2) Requires use of unleaded fuel. (3) Costs are for V-8 (6 cyl. approximately $50 less). |
| 1968-1971 | | | | | | | | | | |
| with air pump | 155.00 | 75.00 | 0 | 0 | 4.8 | 12 | 0.6 | 3.48 | 3.48 | |
| w/o air pump | 70.00 | 65.00 | 0 | 0 | 4.8 | 18 | 0.8 | 1.60 | 1.60 | |
| 1972-1974 | | | | | | | | | | |
| with air pump | 155.00 | 75.00 | 0 | 0 | 3.6 | 12 | 0.4 | 5.04 | 5.04 | |
| w/o air pump | 70.00 | 65.00 | 0 | 0 | 3.6 | 11 | 0.4 | 2.37 | 2.37 | |
| 5 Air bleed + vac. delay | | | | | | | | | | |
| Pre-1968 | 25.00 | 25.00 | 0 | 0 | 3.4 | 10 | 0.34 | 1.34 | 1.34 | |
| 1968-1971 | 25.00 | 25.00 | 0 | 0 | 4.8 | 20 | 1.0 | 0.45 | 0.45 | |
| 6 Air bleed + EGR | | | | | | | | | | |
| Pre-1968 | 55.00 | 25.00 | 1 | 19.00 | 3.4 | 30 | 1.0 | 0.71 | 0.88 | |
| 1968-1971 | 55.00 | 25.00 | 1 | 20.00 | 4.8 | 40 | 1.9 | 0.38 | 0.47 | |
| 7 Catalyst + EGR | | | | | | | | | | (1) Emission reductions at zero miles. Deterioration of emission reduction with mileage not included. (2) Requires use of unleaded fuel. (3) Costs are for V-8 (6 cyl. approximately $50 less). |
| 1968-1971 | | | | | | | | | | |
| with air pump | 190.00 | 75.00 | 3 | 55.00 | 4.8 | 53 | 2.5 | 0.96 | 1.16 | |
| w/o air pump | 105.00 | 65.00 | 3 | 55.00 | 4.8 | 51 | 2.5 | 0.62 | 0.82 | |

[a] All emissions relative to 1975 CVS-C FTP

[b] A negative value indicates a savings; fuel penalty values shown are approximate average values based on limited data with a sometimes wide car-to-car variation.

The cost effectiveness ($/lb of emission reduction) of each of the devices/systems has been evaluated in two ways. First, only the initial installed cost and the incremental 50,000 mile maintenance cost were included in the cost calculation. The second cost effectiveness value includes the fuel penalty cost (or savings), as well as the initial and maintenance costs. This has been done because of the sensitivity of the cost-effectiveness to uncertainties in the fuel economy changes associated with the retrofit device/system, as well as the unit fuel price. This sensitivity is particularly strong for any device, such as the air bleed, for which the fuel savings over 50,000 miles may exceed the installation and maintenance costs. The cost effectiveness, including fuel costs is certainly the most appropriate value to consider in the final analysis, but its uncertainty is also the largest at the present time. Hence, it must be used with care and only after knowing what fuel penalty (or savings) and unit cost have been included in its determination. Further, these cost effectiveness values were determined by dividing the total per vehicle cost for a given emission control strategy by the corresponding values of per vehicle emission reduction for each emission specie (HC, CO, and $NO_x$). Thus they do not represent any attempt to prorate or apportion control costs among the vehicle emissions considered. Some other studies have reported cost effectiveness values that apportion control costs on an arbitrary basis (e.g., by assigning 1/3 of the per vehicle control costs to HC control, CO control, and $NO_x$ control, where a given control system reduces HC, CO, and $NO_x$). For comparison with other study results, the values of Tables 3-10, 3-11, and 3-12 can be easily adjusted by apportioning control costs on the same basis as the study to which it is being compared.

### 3.2.2 Crankcase Emissions

Crankcase emissions have been estimated (Ref. 3-22) to account for approximately 3.4 gm/mi of hydrocarbon emissions from an uncontrolled motor vehicle. Installation of crankcase emission control devices has been mandatory on new cars sold in California since 1961 and nationally since 1968. In addition, California requires a mandatory retrofit of all pre-1961 vehicles with such a device upon change of ownership.

#### 3.2.2.1 Description

Systems to control crankcase emissions are classified as open or closed. In open systems, ventilation air is taken directly from the engine compartment through the oil filler cap and circulated to the intake manifold. However, an open system will allow hydrocarbon evaporative emissions to escape after engine shutdown. Closed systems receive ventilation air through the carburetor air cleaner and are commonly referred to as positive crankcase ventilation (PCV) systems.

#### 3.2.2.2 Installed Cost

The installed cost of the PCV system is \$35 to \$40.

#### 3.2.2.3 Applicability to Vehicle Population

The PCV system, as a retrofit device, would be applicable only to those remaining cars not already equipped with such a device (pre-1961 in California, pre-1963 nationally). This is approximately 8 percent of the vehicle population as of 1 July 1973, and it is estimated to be approximately 5 percent by 1975. As a result, its overall effectiveness as a viable retrofit device is small in terms of total emission reductions.

### 3.2.3 Evaporative Emissions

Carburetor and fuel tank evaporative emission control systems could reduce total vehicle hydrocarbon emissions by approximately 3.0 gm/mi (Ref. 3-22). The use of evaporative emission control systems was initiated in 1970 on new motor vehicles sold in California and in 1971 on new vehicles sold nationally.

#### 3.2.3.1 Description

Two fuel evaporative systems have been designed for new vehicle production use. These are based on two different approaches to fuel vapor recovery. One system stores the fuel vapor in the crankcase and the other stores it in a carbon cannister during soak periods (engine off). The vapors are then purged from the crankcase or cannister when the engine is running.

### 3.2.3.2 Discussion

Evaporative emission control systems are not currently available as a retrofit system and are not a retrofit strategy actively pursued. However, a recent study (Ref. 3-23) investigated the feasibility of an evaporative control retrofit program for the South Coast Air Basin in Southern California. The vehicle retrofit requirements as envisaged in the California study would consist of both fuel tank and carburetor modifications. The possibility of a partial retrofit of controls covering either the carburetor or the fuel tank was also considered.

Fuel tank modifications would require the addition of an expansion tank to the fuel tank, a means of directing evaporative emissions into some convenient storage device, and a vacuum pressure relief gas cap. These modifications to the fuel tank were estimated to cost approximately $60 for domestic cars and $75 for the Volkswagen (the only import evaluated). The carburetor must be rebuilt or replaced with a new carburetor suitable for use in an evaporative emissions control system. Carburetor replacement/rebuilt costs covered a wide range for domestic vehicles, depending on whether a one-, two-, or four-barrel carburetor was involved. A typical layout for a domestic car is shown in Figure 3-2. No carburetor retrofit costs were required for the V-W since these cars (1961 to 1969) were equipped with Solex downdraft carburetors. These carburetors have only an internal vent located at the top of the carburetor throat and vent to an oil bath type air cleaner. This was assumed adequate to control carburetor evaporative losses.

Conclusive data is not available on the desirability of a partial retrofit, i.e., fuel tank or carburetor. Some insight into the relative effectiveness of a partial retrofit can be gained, however, by considering that typical carburetor hydrocarbon evaporative losses (using SHED* techniques) are 10 to 30 gm/test, while fuel tank evaporative losses are typically 50 gm/test (Ref. 3-22).

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*SAE Procedure J171, Sealed Housing for Evaporative Determination (SHED) technique.

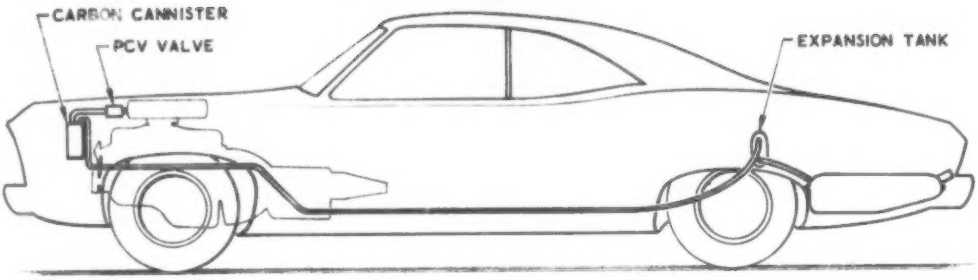
CARBON CANNISTER
PCV VALVE
EXPANSION TANK

Figure 3-2. Location of Evaporative Control System Components (Ref. 3-23)

### 3.2.3.3 Installed Cost

Based on estimates of the vehicle population and the distribution of engine (and carburetor) types in the vehicle population in the South Coast Air Basin, weighted (by vehicle age, make, and model) installation costs were derived (Ref. 3-23) for this retrofit system. If the carburetor replacement was required, the weighted average installed cost (including fuel tank modifications) was found to be $117. If rebuilding the carburetor was feasible, the cost was estimated to be $95.

### 3.2.3.4 Maintenance

Annual maintenance costs to replace the charcoal cannister were estimated to be approximately $5.

### 3.2.3.5 Applicability to Vehicle Population

This retrofit approach is potentially applicable to all pre-1971 vehicles nationally (pre-1970, California). However, the myriad of vehicle configurations make this an extremely difficult retrofit approach to implement.

## 3.3 IMPLEMENTATION OF RETROFIT STRATEGIES FOR LIGHT DUTY VEHICLES

### 3.3.1 Introduction

The implementation of a retrofit strategy must take a number of factors into consideration. In general, these would include the evaluation, selection, and certification of devices/systems; analysis of the costs associated with each device, together with any attendant financing strategies; and the development of installation strategies and schedules.

Many of the factors to be considered are similar to those attendant to the implementation of an inspection/maintenance program. These basic considerations were discussed at length in Section 2.7 and are not repeated here in the interest of brevity. Those implementation aspects more singularly related to retrofit programs are summarized below.

### 3.3.2 Selection and Certification

The selection of emission control devices/systems should, of course, be tailored to meet the ambient air quality requirements of a particular State or Air Quality Control Region (AQCR). If, for example, the primary problem is one of reduction of CO, a relatively simple and inexpensive approach such as the air bleed device may be adequate. If, on the other hand, a significant reduction of all three pollutants must be achieved, then it may be necessary to consider one of the combination systems such as the oxidation catalyst and EGR. Concurrent with this, the applicability of the device/system to the vehicle population within the region of interest must also be considered.

The emission reduction potential of a given device/system should be based on a statistically significant sample size. To this end, the EPA has published a set of proposed voluntary protocols for the evaluation of exhaust emission retrofit devices for motor vehicles (Ref. 3-24). The purpose of that approach is to provide a centralized evaluation program to compile technical data on various exhaust emission control devices. The program will primarily address the effects of emission control potential, applicability, durability and driveability, and fuel consumption of specific retrofit devices presented for evaluation. Techniques are presented in the protocol whereby the number of vehicles to be tested will be such that the determination of the mean percent reduction (or increase) of HC, CO, and $NO_x$ can be evaluated within a band of ±5 percent at the 90 percent confidence level.

In addition to the emission reduction capability of a device/system, other factors that must be considered in the selection and certification are the durability or emission reduction effectiveness at extended mileage, the impact on the driveability of the vehicle, possible safety considerations, and the effect of the device/system on the fuel economy. It is also necessary to be certain that the device is commercially available in sufficient quantities to meet the requirements of a given State or AQCR. Consideration must also be given to whether the device will be installed in private garages or in State-licensed facilities. In the latter case, licensing procedures would have to be designed and implemented.

### 3.3.3 Cost and Financing

The method of financing the initial cost must also be established for the retrofit device/system selected. In the case of those devices costing $20 to $35, this probably could be best treated as a one-time cash expenditure by the vehicle owner. In the case of the more expensive catalytic converter systems, however, this approach could impose a financial burden on many car owners and other alternatives must be evaluated and considered.

### 3.3.4 Implementation Scheduling

Several alternatives have been suggested as possible options for implementing a retrofit program. It must be emphasized that the most effective implementation strategies will depend upon several factors, including the number of vehicles to be retrofitted, the availability of the devices in sufficient quantities, the availability of competent servicemen to make the proper installation, the administrative mechanisms within a given State or AQCR to ensure that the installations are made properly, and a consistently strong will to accomplish retrofit at all levels of government.

The most viable implementation plans from an administrative point of view are those involving vehicle registrations, and this could be accomplished either at the time of annual registration or on change of ownership. A third strategy (to be used for $NO_x$ retrofit in California) is to stagger the retrofit program over a 10-month period with the implementation date (month) being determined by the last digit of the vehicle license plate. The California $NO_x$ retrofit program for 1966-1970 vehicles has been reinstated (following a previous one-year delay).

## 3.4 RETROFIT EMISSION CONTROL FOR TRUCKS

In several studies the same engine modifications and devices that were discussed in Sections 3.1 through 3.3 for retrofit to light duty vehicles were also considered for use on trucks (GVW > 6000 lb). However, the circumstances surrounding their use on trucks are sufficiently different that it is advisable to consider retrofit strategies for trucks separately. These considerations are summarized in this section, with the discussion divided into the following parts: (1) the general characteristics of truck populations that are important in the evaluation of retrofit control strategies, (2) the effectiveness of various retrofit emission control approaches and devices for heavy duty gasoline and diesel engines, (3) the cost effectiveness of retrofit strategies, and (4) implementation considerations.

There have been several recent studies that addressed the characteristics of a separate vehicle class (GVW = 6000 to 10,000 or 14,000 lb) within the overall truck classification of GVW > 6000 lb. However, the data with regard to retrofit are not sufficiently explicit to justify a separate consideration of this class at this time.

### 3.4.1 General Considerations

Various characteristics of the truck populations were discussed in Section 2.8 in connection with the inspection/maintenance of such vehicles. It was found that the heavy duty class of trucks is quite nonhomogeneous with respect to weight, size, use, and mode of operation and maintenance, and that the emissions (gm/mi) from heavy duty vehicles increase significantly with increasing vehicle weight and, in general, are much higher than for light duty vehicles. This difference in emissions has widened in recent years and should continue to do so in the foreseeable future as long as the emission standards for light duty vehicles are tightened to a greater extent than those for heavy duty engines. Hence, the potential for emission reduction from the retrofit of heavy duty vehicles may be larger than for light duty vehicles. This, coupled with the fact that the average lifetimes of trucks are significantly longer than those of passenger cars (Ref. 3-25), indicates that retrofit strategies for heavy duty vehicles have the potential to be effective in reducing mobile source emissions, especially in those urban areas such as Los Angeles, New York City, Chicago, etc., which have large truck populations. Conversely, if excessive hardware and/or emission control deterioration were encountered, this would of course reduce the effectiveness of a truck retrofit strategy.

In assessing the effectiveness of a retrofit strategy in a given AQCR, information is needed concerning the baseline emissions of vehicles in the various heavy duty weight classes, the number of vehicles in each class and model year in the region, and the miles traveled (in a given reference period) by the vehicles in each class. The latter two types of information vary significantly from region to region.

The baseline truck emissions, which depend on weight, model year, and fuel type, are common to all AQCRs, except for California and those operated at high altitude. There are much less emissions data available for trucks than for passenger cars (Refs. 3-26 through 3-28) and, in addition, much of the available truck data pertains to recent model vehicles (1970-73) and vehicles in the GVW < 14,000 lb class. Also, many of the heavier trucks (GVW > 26,000 lb) are tractor-trailer combinations that often use diesel rather than gasoline engines.

For the heavy duty vehicle class as a whole (GVW > 6000 lb), estimates of emission characteristics and deterioration rates by applicable model year have been provided by EPA in Ref. 3-25. However, with regard to emission characteristics for specific subgroups within the overall heavy duty vehicle class, a significant volume of data regarding emissions variations by model year is available only for the GVW category between 6000 and 10,000 lb. Average baseline HC, CO, and $NO_x$ emissions for this class of vehicles for model years between 1965 and 1973 are given in Table 3-13. There is considerable scatter in this data (Refs. 3-26 and 3-29), and the values given in Table 3-13 represent an average of data from the baseline

Table 3-13. Emission Values for Medium Duty Vehicles by Model Year (Ref. 3-29)

| Model Year | Emissions (gm/mi) | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| **Pickups, Vans, and Panel Trucks (6000 to 10,000 lb GVW)** | | | |
| 1973 | 4.25 | 49.22 | 4.95 |
| 1972 | 4.46 | 51.56 | 7.49 |
| 1971 | 5.87 | 65.52 | 8.17 |
| 1970 | 5.93 | 71.78 | 7.63 |
| 1969 | 7.31 | 93.59 | 6.37 |
| 1968 | 10.58 | 125.35 | 5.61 |
| 1967 | 11.07 | 126.15 | 5.20 |
| 1966 | 12.40 | 110.95 | 5.75 |
| 1965 | 10.62 | 75.51 | 6.49 |
| **Conventional Motor Homes (6000 to 14,000 lb GVW)** | | | |
| 1970 to 1973 | 8.91 | 116.27 | 12.57 |
| Pre-1970 | | Insufficient data | |
| **Chassis and Other Trucks (6000 to 14,000 lb GVW)** | | | |
| 1970 to 1973 | 6.78 | 72.05 | 8.52 |
| Pre-1970 | 12.20 | 113.82 | 9.43 |

emission characterization program recently conducted by EPA (Refs. 3-29 and 3-30). For trucks in other weight categories, only scattered data points are available (Refs. 3-27 and 3-28). In general, it can be stated that the emissions of all three pollutants for a given model year increase with increasing vehicle weight (Ref. 3-29) and that HC and CO tend to decrease for model years after 1970 (relative to pre-1970 levels) for all the truck categories.

### 3.4.2 Retrofit of Gasoline-Fueled Trucks

#### 3.4.2.1 Introduction

The gasoline engines used in many trucks, especially those with GVW less than 14,000 lb are basically the same as those used in standard-size passenger cars. Hence, the emission control systems on these engines have reflected both the effect of tightened heavy duty engine and light duty vehicle emission standards. The progression of emission control systems on light duty vehicles has been summarized previously in Table 3-1. As indicated in Table 3-14, these same emission control systems* are now being used on some 1973 heavy duty vehicles. Hence, in retrofitting heavy duty vehicles, it is reasonable to consider the use of the same retrofit devices and control technologies for light duty vehicles that have been discussed in detail in Sections 3.1 through 3.3. Since the power-to-weight ratio of trucks, especially those with GVW > 10,000 lb, is much less than that of passenger cars, the emission reduction effectiveness of these retrofit devices when used on trucks could be quite different from that of the same device on a car. In addition, there are questions concerning what emission test cycle is appropriate for the various categories of heavy duty vehicles and how the different retrofit approaches are affected by the

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*A PCV system is required nationally, while an evaporative control system is required by California if fuel tank capacity is less than 50 gallons.

Table 3-14. Group Representative Vehicle-Engine Combinations
(Emission Control Devices - 1973 Models) (Ref. 3-30)

| Vehicle Type | Make | Model | Engine | Emission Controls | | | Notes |
|---|---|---|---|---|---|---|---|
| | | | | Crankcase | Evaporative | Exhaust | |
| Pickup/camper | Chev./GMC | C20/C25 | V8-350 | PCV | GMECS | CCS[a] | 1 |
| | I-H | 1210 | V8-345 | PCV | CAN | EM,[a] EGR, TLD | 1, 4, 6 |
| Van/passenger van | Ford | E300 | V8-302 | PCV | CC | IMCO[a] | 1 |
| Multistop | Chev./GMC | P30/P35 | I6-250 | PCV | -- | CCS | 2 |
| Chassis | Chev./GMC | C20/C25 | V8-454 | PCV | GMECS | CCS, AI | 1, 3 |
| | Ford | F350 | V8-360 | PCV | CC | IMCO, EGR | 1, 4 |
| | Ford | F500 | V8-330 | PCV | CC | IMCO | 1 |
| Motor home | Dodge | M300/R400 | V8-318 | PCV | CAN | EM | 1, 5 |

[a] EM, CCS, and IMCO are basically engine modifications (carburetor, choke, compression ratio, and spark retard) to reduce emissions.

Notes:
1 Evaporative controls only on California vehicles with fuel tanks ≤50 gallons.
2 This engine not sold in California.
3 Air injection (AI) only on California vehicles.
4 Exhaust gas recirculation (EGR) only on California vehicles.
5 Electronic Ignition on California vehicles, otherwise optional.
6 Throttle limiting device (TLD) only on California vehicles.

test cycle. However, once an air-quality-related test procedure is developed for heavy duty vehicle retrofit evaluation, that procedure should be used to evaluate effectiveness.

The performance of retrofit devices will be considered relative to the following emission test cycles: (1) 1975 CVS FTP, (2) an urban short test cycle, and (3) a multimode (steady-state) engine test cycle. One of these cycles should be appropriate for any heavy duty vehicle application or retrofit program. The 1975 CVS FTP, which utilizes the EPA Urban Dynamometer driving schedule, is appropriate for the smaller of the heavy duty vehicles (GVW < 14,000 lb) with inertia weights of 10,000 lb or less. These vehicles usually have a power-to-weight ratio that permits them to be driven much like light duty vehicles. The short urban cycles, such as the New York City Quick Cycle and the New Jersey Accelerate, Cruise, Idle, Decelerate (ACID) cycle (see Fig. 2-1), have a maximum cruise velocity of 30 mph and a considerable period of idle. These cycles may be appropriate for heavy delivery or sanitation trucks (GVW > 20,000 lb) operating in a congested urban area such as Manhattan. Finally, since heavy duty engines are certified relative to a multimode engine test cycle, it seems reasonable to evaluate retrofit devices/systems for such engines on the same engine cycle. Several engine cycles are currently in use, namely, the 9, 13, and 23-mode cycles involving emissions testing at one or more rpm and a range of engine loads. Both the composite and modal emissions data from the testing of retrofit devices on heavy duty engines may be useful to estimate their performance on the various classes of trucks.

There are three primary sources of information relative to the effectiveness of retrofit devices on heavy duty vehicles: (1) the continuing study by the New York City Department of Air Resources (Ref. 3-31), (2) EPA tests of retrofitted medium duty trucks (Ref. 3-32), and (3) the engine dynamometer tests of retrofitted heavy duty engines by the Southwest Research Institute (SWRI). The study by the New York City Department of Air Resources is directly applicable to the present discussion, as it involves retrofitting a number of 1969-1971 trucks (GVW between 6000 and 47,000 lb) with emission control devices/systems identical to those tested previously on light duty vehicles. Vehicle emissions measurements are made before and after the devices are installed, and a durability test program is also planned for the most promising devices. The lighter trucks (GVW < 10,000 lb) are tested using the 1972 CVS-H test procedure, while the heavier trucks are tested using the New York City Quick Cycle, which is thought to be more appropriate than the 1972 CVS-H for heavy truck operation in congested areas. One important limitation of the New York City (NYC) retrofit program is that all the data were taken on a light duty dynamometer, which means that the maximum inertia weight that could be simulated was 5500 lb. Because of this, the NYC data do not show the true effects of vehicle weight on retrofit device performance. In addition, since the NYC program to date has involved many retrofit devices, each of which was tested on only a few vehicles at most in each weight class, it is difficult to separate out the effects of test cycle, vehicle size, and device characteristics. The NYC results are, however, helpful in developing a general format for examining retrofit device performance, and in some cases are the only source of pertinent emission reduction information. The EPA and SWRI data (Refs. 3-32 and 3-33) can be used to interpret and augment the NYC retrofit data.

In the EPA program, emission measurements were made on two 1972 trucks (5500 to 7000 lb inertia weight), using the 1975 CVS-CH FTP, as well as at selected steady-state modes (idle to 60 mph cruise). The SWRI studies involved two 1972 V-8 engines (General Motors 350 CID and Ford 361 CID) often used in heavy duty vehicles. These engines, which were retrofitted (or modified) using various approaches to reduce their emissions, were tested using the 23-mode engine test cycle (Table 3-15) that includes a wide range of operating conditions. This engine test cycle is particularly applicable to heavy trucks, as it emphasizes high load conditions near maximum engine torque. Tabulated modal data for several engine modifications and retrofits are given in Ref. 3-34, as well as the composite cycle emissions levels, for each of the engine configurations. The steady-state EPA and

Table 3-15. **Experimental 23-Mode Emissions Test Schedule (Heavy Duty Gasoline Engines) (Ref. 3-33)**

| Mode | Engine Speed (rpm) | Power Out (%)[a] | Mode Time | Cumulative Time | Weighting Factor |
|---|---|---|---|---|---|
| 1 | Idle | 0 | 3 | 3 | 0.07 |
| 2 | 1200 | 2 | 3 | 6 | 0.06 |
| 3 | 1200 | 8 | 3 | 9 | 0.06 |
| 4 | 1200 | 18 | 3 | 12 | 0.05 |
| 5 | 1200 | 25 | 3 | 15 | 0.03 |
| 6 | 1200 | 50 | 3 | 18 | 0.06 |
| 7 | 1200 | 75 | 3 | 21 | 0.00 |
| 8 | 1200 | 82 | 3 | 24 | 0.04 |
| 9 | 1200 | 92 | 3 | 27 | 0.00 |
| 10 | 1200 | 100 | 3 | 30 | 0.00 |
| 11 | Idle | 0 | 3 | 33 | 0.07 |
| 12 | 1200 | 0 (CT)[b] | 12 | 45 | 0.12 |
| 13 | 2300 | 100 | 3 | 48 | 0.025 |
| 14 | 2300 | 92 | 3 | 51 | 0.055 |
| 15 | 2300 | 82 | 3 | 54 | 0.035 |
| 16 | 2300 | 75 | 3 | 57 | 0.06 |
| 17 | 2300 | 50 | 3 | 60 | 0.06 |
| 18 | 2300 | 25 | 3 | 63 | 0.00 |
| 19 | 2300 | 18 | 3 | 66 | 0.065 |
| 20 | 2300 | 8 | 3 | 69 | 0.00 |
| 21 | 2300 | 2 | 3 | 72 | 0.00 |
| 22 | Idle | 0 | 3 | 75 | 0.08 |
| 23 | 2300 | 0 (CT)[b] | 3 | 78 | 0.06 |

[a] Observed at the flywheel, percent of maximum at a given engine rpm.

[b] Power out is zero. Engine requires motoring in this mode.

SWRI engine cycle data are summarized in Tables 3-16 and 3-17. In the case of the SWRI tests (Table 3-17), it was found that both spark retard and a 10-percent cold EGR flow rate resulted in sizeable reductions in maximum hp output at test conditions of 1200 and 2300 rpm. For example, with the Ford V-8 engine, a spark retard of 6 degrees reduced the maximum hp about 13 percent, and a cold EGR of 10 percent reduced the maximum about 18 percent. These results and the vehicle cycle emissions measurements

Table 3-16. Summary of Emission Reductions at Various Steady-State Operating Conditions Using Retrofitted Catalyst and EGR Systems (Ref. 3-32)

| Operating Condition[a] | % Reduction[b] at Zero System Mileage | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| Idle | | | |
| GM 350 CID, 6500 lb | 85 | 98 | - |
| Chrysler 318 CID, 7000 lb | 98 | 99 | - |
| 15 mph | | | |
| GM 350 CID, 6500 lb | 87 | - | 48 |
| Chrysler 318 CID, 7000 lb | 93 | 98 | 83 |
| 30 mph | | | |
| GM 350 CID, 6500 lb | 88 | 91 | 65 |
| Chrysler 318 CID, 7000 lb | 90 | 90 | 67 |
| 60 mph | | | |
| GM 350 CID, 6500 lb | 93 | 91 | 48 |
| Chrysler 318 CID, 7000 lb | 98 | 95 | 57 |

[a] Vehicle operating in mode and inertia weight indicated — 6500 lb, 50 mph, road load, 32 hp; 7000 lb, 50 mph, 37 hp

[b] Emission reduction using a catalyst and EGR; any effect of catalyst deterioration is not included.

Table 3-17. Summary of SWRI Heavy Duty Engine Retrofit Data (Ref. 3-33)

| Engine Tested | Retrofit Modification | Fuel Consumption (lb/bhp-hr) | Emissions (gm/bhp-hr)[a] | | |
|---|---|---|---|---|---|
| | | | HC | CO | $NO_x$ |
| Ford V-8 361 CID | a. None (baseline engine) | 0.72 | 9.2 | 72 | 8.7 |
| | b. Engine modifications | | | | |
| | 1. Six-degree spark retard | 0.86 | 8.5 | 110 | 5.5 |
| | 2. Leaner air/fuel ratio (from 0.056-in. dia. main jets to 0.51-in. dia.) | 0.77 | 8.65 | 44 | 9.7 |
| | c. Baseline engine plus: | | | | |
| | 1. Ten percent "cold" EGR | 0.88 | 10.1 | 143 | 2.2 |
| | 2. Oxidation catalyst plus air injection | 0.78 | 1.43 | 49 | 6.22 |
| | 3. Oxidation catalyst plus air injection plus 5 to 10 percent "hot"[b] EGR | 0.83 | 1.31 | 19 | 4.1 |
| GM V-8 350 CID | a. None (baseline engine) | 0.63 | 7.3 | 56 | 8.6 |
| | b. Engine modifications | | | | |
| | 1. Eight-degree spark retard | 0.79 | 6.2 | 66 | 6.0 |
| | 2. Leaner air/fuel ratio (from 0.073-in. dia. main jets to 0.068-in. dia.) | 0.64 | 7.2 | 32 | 8.8 |
| | c. Baseline engine plus: | | | | |
| | 1. Ten percent "cold" EGR | 0.75 | 7.2 | 37 | 2.6 |
| | 2. Oxidation catalyst plus air injection | 0.61 | 0.85 | 18 | 8.1 |
| | 3. Oxidation catalyst plus air injection plus 5 to 10 percent "hot"[b] EGR | 0.67 | 2.1 | 16.6 | 6.2 |

[a] 23-Mode composite values.

[b] Light duty vehicle approach using exhaust manifold crossover to extract exhaust and a vacuum-actuated EGR valve.

made by EPA and NYC form the data base currently available for the retrofit emission control system characteristics (emissions reduction and fuel economy changes) given in the next section. In a few cases, expecially for pre-1971 model year vehicles, light duty vehicle retrofit emissions data are also used to estimate system characteristics.

### 3.4.2.2 Emission Reduction Potential and the Cost Effectiveness of Exhaust Emission Control Systems

The EPA has provided initial estimates of reductions in exhaust emissions achievable through the installation of various types of retrofit devices for trucks (6000 to 10,000 lb GVW) (Table 3-18). These estimates were provided in the Addendum to Appendix N of 40 CFR 51 (Federal Register, Vol. 38, No. 110 (Friday, June 8, 1973) for transportation control measure

Table 3-18. Estimated Emission Reductions for Retrofit of the 6000 to 10,000 GVW Class[a]

| Retrofit Option | Average Reduction per Vehicle (%)[b] | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| Exhaust gas recirculation (pre-1973, plus 1973 and 1974 models without EGR) | 0 | 0 | 40 |
| Oxidation catalysts (1968 and later not originally equipped with catalysts) | 50 | 50 | 0 |
| Air bleed to intake manifold (pre-1974 or pre-1973 California vehicles) | 15 | 30 | 0 |

[a] Appendix N of 40 CFR 51 (Federal Register, Vol. 38, No. 110 (Friday, June 8, 1973).

[b] Reductions are to be applied to a maintained vehicle baseline (i.e., applied after emission reduction claimed for inspection/maintenance)

planning purposes. The data and discussions presented below are supplementary to that of Appendix N and are a summarization of current estimates related to the emission reduction performance and cost aspects of specific retrofit approaches for the truck GVW spectrum from 6000 lb to 26,000 lb.

The same retrofit emission control systems that were discussed in Section 3.2 for light duty vehicles are considered for heavy duty vehicle applications in this section. Estimated values for the emission reductions and fuel economy changes associated with each of the retrofit systems are given in Table 3-19 for the three test procedures (1975 FTP, short urban cycle, and 23-mode engine cycle) appropriate to the various categories of trucks. The values shown in Table 3-19 represent averages from the EPA, NYC, and SWRI data previously discussed. Considerable uncertainty exists regarding many of the values shown, but sufficient data does not exist to evaluate the uncertainties quantitatively. In the absence of appropriate truck data, light duty vehicle retrofit data were used and must be treated as an estimate only. This latter approach was necessary primarily in the case of engine modification for pre-1971 vehicles. The model years for which each of the retrofit approaches is applicable are indicated in Table 3-19. Post-1970 trucks were considered to be emissions controlled, while earlier model years are termed uncontrolled.

The effect of the emissions test procedure on the performance of the various retrofit devices/systems is due for the most part to differences in engine loads experienced during the test cycles. High load test conditions are particularly important if they require operation of the high-speed power circuit of the carburetor because that results in higher HC and CO emissions and higher specific fuel consumption than would normally be the case. Any retrofit approach (such as spark retard or EGR) that significantly degrades engine power output forces early use of the carburetor power circuit, resulting in lower emission reductions and a significant fuel economy penalty. Thus, the influence of engine load on retrofit control system performance can be very important and must be kept in mind when evaluating the use of such systems on vehicles of significantly different GVW.

Table 3-19. Estimated Emission Reduction and Fuel Penalty Characteristics of Retrofit Emission Control Systems for Trucks

| Retrofit Approaches | Applicable to | Percent Reduction[a] | | | | Source for Estimate |
|---|---|---|---|---|---|---|
| | | Emissions | | | Fuel Economy | |
| | | HC | CO | $NO_x$ | | |
| Engine modifications | | | | | | |
| Lean carburetion[b] | Pre-1971 | | | | | |
| 1975 FTP | | 15 | 40 | -5 | -5 | NYC (Ref. 3-31) & LDV data[c] |
| Urban cycle | | 20 | 55 | -5 | -3 | NYC (Ref. 3-31) |
| Engine cycle | | 5 | 40 | -5 | 5 | SWRI (Ref. 3-33) |
| Retarded timing[d] | | | | | | |
| 1975 FTP | | 20 | 0 | 35 | 8 | LDV data |
| Urban cycle[e] | | NA[f] | NA | NA | NA | -- |
| Engine cycle[e] | | 10 | -35 | 35 | 20 | SWRI (Ref. 3-33) |
| EGR | Post-1970 | | | | | |
| 1975 FTP | | 0 | -5 | 40 | 6 | LDV data |
| Urban cycle | | NA | NA | NA | NA | -- |
| Engine cycle | | -15 | -10 | 35 | 15 | SWRI (Ref. 3-33) |
| EGR + lean carburetion | Pre-1971 | | | | | |
| 1975 FTP | | 10 | 30 | 30 | 0 | NYC (Ref. 3-31) |
| Urban cycle | | NA | NA | NA | NA | -- |
| Engine cycle | | -10 | 30 | 35 | 10 | SWRI (Ref. 3-34) & LDV data |
| Catalyst w/air pump[g] | Post-1970 | | | | | |
| 1975 FTP | | 80 | 80 | -5 | 0 | NYC (Ref. 3-31) |
| Urban cycle | | 85 | 85 | 0 | 4 | NYC (Ref. 3-31) |
| Engine cycle | | 85 | 70 | -5 | 3 | SWRI (Ref. 3-33) |
| Catalyst w/air + EGR[g] | Post-1970 | | | | | |
| 1975 FTP | | 80 | 80 | 40 | 6 | Ref. 3-32 |
| Urban cycle | | NA | NA | NA | NA | -- |
| Engine cycle | | 75 | 70 | 40 | 10 | SWRI (Ref. 3-33) |

[a] Minus sign means an increase; this applies to fuel consumption also.

[b] Increase in mean air/fuel ratio of about one due to air bleed or lean carburetion.

[c] In all cases, LDV data refers to light duty vehicle retrofit emissions data previously developed in Section 3.2.

[d] Retarded timing change of 4 to 6 degrees.

[e] Urban cycle is the NYC Quick Cycle; engine cycle is the 23-mode engine test cycle.

[f] No data available.

[g] All values correspond to catalysts at low mileage; deterioration effects should be accounted for separately.

The cost effectiveness of selected* retrofit emission control systems was studied for the three truck GVW categories (6000-10,000 lb, 10,000-20,000 lb, and 20,000-26,000 lb). Two retrofit strategies for both precontrolled and controlled vehicles were considered for each of the GVW categories. One of the strategies is intended to reduce only HC and CO emissions, while the second controls $NO_x$ emissions as well as HC and CO. The baseline model year for the precontrolled vehicles was taken to be 1968, and for the controlled vehicles, 1972. It was assumed that the 1975 FTP was appropriate for evaluating emissions from trucks of 6000 to 10,000 lb GVW, and that the 23-mode engine cycle was most suitable for both the 10,000 to 20,000 lb and 20,000 to 26,000 lb categories. The baseline emissions, emission reduction factors, and fuel economy changes for each retrofit strategy, test procedure, and truck category were obtained from Tables 3-13 and 3-19. In assessing the cost effectiveness of each case, the same general approach as followed in Section 3.2.1.7 for light duty vehicles was used. The incremental maintenance and fuel costs due to retrofit were based on 50,000 miles of truck operation to facilitate direct comparisons with light duty vehicle results that were also based on 50,000 miles. All the costs, including the initial cost of installation, were determined by starting with light duty vehicle cost values and adding appropriate cost increments to account for the larger sizes and/or increased durability requirements of heavy duty vehicles. The results of the cost-effectiveness study are given in Table 3-20. Note that cost-effectiveness values ($/lb) in the table are given excluding and including the effect of fuel economy changes due to retrofit devices. Since the fuel consumption of heavy duty vehicles is much greater than for light duty vehicles, the effects of a fuel economy penalty due to retrofit on the cost effectiveness is even greater for trucks than for passenger cars. Hence,

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*The more likely combinations of retrofit systems for both precontrolled and controlled trucks were selected for the cost-effectiveness study.

## Table 3-20. Estimated Cost Effectiveness of Various Retrofit Strategies for Gasoline-Fueled Trucks

| | Costs[a] | | | Emission Reductions and Cost Effectiveness | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | HC | | | CO | | | $NO_x$ | | |
| Retrofit Strategies | Initial Cost ($) | Maintenance Cost ($) | Incremental Fuel Cost[b] ($) | Baseline[c] (gm/mi) | Reduction (%) | $/lb[d] | Baseline (gm/mi) | Reduction (%) | $/lb | Baseline (gm/mi) | Reduction (%) | $/lb |
| Precontrolled trucks | | | | | | | | | | | | |
| Lean carburetion[e] | | | | | | | | | | | | |
| 6 - 10[f] | 25 | 25 | -125 | 10.8 | 15 | 0.28, -[g] | 125 | 40 | 0.009, - | 8.8 | -5 | - |
| 10 - 20 | 40 | 25 | +208 | 16.3 | 5 | 0.72, 3.0 | 190 | 40 | 0.008, 0.032 | 14.7 | -5 | - |
| 20 - 26 | 40 | 25 | +278 | 22.4 | 5 | 0.53, 2.8 | 262 | 40 | 0.006, 0.030 | 20.3 | -5 | - |
| Lean carburetion + EGR | | | | | | | | | | | | |
| 6 - 10 | 50 | 50 | 0 | 10.8 | 10 | 0.84, 0.84 | 125 | 30 | 0.025, 0.024 | 8.8 | 30 | 0.34, 0.34 |
| 10 - 20 | 65 | 50 | +417 | 16.3 | -10 | - | 190 | 30 | 0.018, 0.085 | 14.7 | 35 | 0.20, 0.94 |
| 20 - 26 | 65 | 50 | +557 | 22.4 | -10 | - | 262 | 30 | 0.013, 0.077 | 20.3 | 35 | 0.15, 0.86 |
| Controlled trucks | | | | | | | | | | | | |
| Oxidation catalyst with air[h] | | | | | | | | | | | | |
| 6 - 10 | 150 | 75 | 0 | 5.7 | 80 | 0.45, 0.45 | 66 | 80 | 0.039, 0.039 | 8.0 | -5 | - |
| 10 - 20 | 250 | 150 | +125 | 8.6 | 85 | 0.50, 0.65 | 100 | 70 | 0.052, 0.068 | 13.4 | -5 | - |
| 20 - 26 | 250 | 150 | +167 | 11.8 | 85 | 0.36, 0.51 | 138 | 70 | 0.041, 0.058 | 18.5 | -5 | - |
| Oxidation catalyst with air[h] + EGR | | | | | | | | | | | | |
| 6 - 10 | 185 | 100 | +150 | 5.7 | 80 | 0.57, 0.87 | 66 | 80 | 0.049, 0.075 | 8.0 | 40 | 0.81, 1.24 |
| 10 - 20 | 285 | 175 | +417 | 8.6 | 75 | 0.65, 1.25 | 100 | 70 | 0.060, 0.113 | 13.4 | 40 | 0.78, 1.49 |
| 20 - 26 | 285 | 175 | +557 | 11.8 | 75 | 0.57, 1.04 | 138 | 70 | 0.043, 0.096 | 18.5 | 40 | 0.57, 1.25 |

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[a] Costs for 50,000 miles of vehicle operation.

[b] Baseline fuel economy values used were 10, 6, 4.5 mpg for the truck groups in the 6000 to 10,000, 10,000 to 20,000, and 20,000 to 26,000 lb GVW class, respectively. Unit fuel cost was $0.50/gal.

[c] Baseline emissions are for the 1968 model year in case of precontrolled vehicles and 1972 in case of controlled vehicles.

[d] First value excludes the effect of incremental fuel costs, while the second value includes the change in fuel costs.

[e] Increase in average air/fuel ratio of about one unit.

[f] GVW in 1000 lb.

[g] Cost effectiveness is not meaningful if retrofit system results in an increase in emissions of a particular pollutant or fuel savings cause the net cost to be negative; hence, in these cases, no value for $/lb is shown.

[h] All emission reductions correspond to a "new" catalytic converter; deterioration is not included.

a relatively small error or uncertainty in the fuel economy penalty can significantly affect the cost effectiveness of a given retrofit system.

It is of interest to compare the cost effectiveness of various retrofit emission control strategies for vehicles of different GVW (from passenger cars to 26,000-lb trucks). This comparison is shown in Table 3-21 using the results previously given in Tables 3-10 to 3-12 and 3-20. The following conclusions can be drawn from Table 3-21.

a. All the retrofit emission control strategies for trucks less than 10,000-lb GVW are at least as cost effective as they are for light duty vehicles.

b. The oxidation catalyst with air injection retrofit system maybe as cost effective for heavier vehicles (GVW up to 26,000 lb) as for light duty vehicles. In general, the cost effectiveness for HC and CO emission reduction increases with increasing GVW, assuming that catalyst durability does not become a problem at high engine loads.

c. Lean carburetion (or air bleed) retrofit is less cost effective for precontrolled trucks greater than 10,000 lb GVW than for trucks less than 6000 to 10,000 lb GVW and light duty vehicles.

d. The fuel penalty due to EGR at high engine loads is the dominant factor in reducing the cost effectiveness of retrofit emission control systems having $NO_x$ control on trucks greater than 10,000 lb GVW. $NO_x$ control on heavy vehicles is significantly more difficult than on lighter vehicles because of the fuel penalty and output power degradation associated with EGR and spark retard near maximum power.

### 3.4.3 Retrofit of Diesel Powered Trucks

Many of the larger trucks (GVW > 26,000 lb) are powered by diesel engines. Most of these engines are of the open-chamber, direct-injection type, which have HC and CO emissions that are much lower (65 to 90 percent less) and $NO_x$ emissions that are about 50 percent higher than would result if a gasoline engine of comparable power were used in the vehicle. In addition to the gaseous pollutants, diesel engines can also exhaust smoke, aldehydes, and odorous compounds that are objectionable. Since

Table 3-21. Comparison of the Estimated Cost Effectiveness of Various Retrofit Strategies on Vehicles of Differing GVW

| Vehicle | Cost Effectiveness ($/lb) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | HC | | | | CO | | | | $NO_x$ | | | |
| | LDV[a] | 6-10[b] | 10-20 | 20-26 | LDV | 6-10 | 10-20 | 20-26 | LDV | 6-10 | 10-20 | 20-26 |
| Precontrolled (pre-1971) | | | | | | | | | | | | |
| Lean carburetion | | | | | | | | | | | | |
| Excluding fuel | 0.23 | 0.28 | 0.72 | 0.53 | 0.007 | 0.009 | 0.008 | 0.006 | - | - | - | - |
| Including fuel | +[c] | + | 3.0 | 2.8 | + | + | 0.032 | 0.030 | - | - | - | - |
| Lean carburetion + EGR | | | | | | | | | | | | |
| Excluding fuel | 0.24 | 0.84 | -[c] | - | 0.010 | 0.024 | 0.018 | 0.013 | 0.53 | 0.34 | 0.20 | 0.15 |
| Including fuel | 0.32 | 0.84 | - | - | 0.015 | 0.024 | 0.085 | 0.077 | 0.70 | 0.34 | 0.94 | 0.86 |
| Controlled (post-1971) | | | | | | | | | | | | |
| Oxidation catalyst[d] with air | | | | | | | | | | | | |
| Excluding fuel | 0.62 | 0.45 | 0.50 | 0.36 | 0.05 | 0.039 | 0.052 | 0.041 | 3.6 | - | - | - |
| Including fuel | 0.62 | 0.45 | 0.65 | 0.50 | 0.05 | 0.039 | 0.068 | 0.058 | 3.6 | - | - | - |
| Oxidation catalyst[d] with air + EGR | | | | | | | | | | | | |
| Excluding fuel | 0.72 | 0.57 | 0.65 | 0.47 | 0.06 | 0.049 | 0.06 | 0.043 | 0.95 | 0.81 | 0.78 | 0.57 |
| Including fuel | 0.88 | 0.87 | 1.25 | 1.04 | 0.07 | 0.075 | 0.113 | 0.196 | 1.2 | 1.24 | 1.49 | 1.25 |

[a] Light duty vehicles, GVW ≤ 6000 lb.

[b] 6000 to 10,000 lb GVW category.

[c] Plus indicates net cost savings; minus indicates retrofit device increased emissions.

[d] No catalyst deterioration included.

the HC and CO emissions of the diesel engine are quite low, it is possible that any diesel retrofit program would be involved only with the reduction of $NO_x$ emissions. Controlling smoke from diesels is not a matter of retrofit, but rather one of proper adjustment and maintenance of the fuel injection and timing systems. Unfortunately, the exhaust of odorous compounds is characteristic of all lean-burning engines. However, two approaches for alleviating the odor problem for such engines are known. These approaches are the use of low-sac volume in injector tips and fuel-limiting devices.

There have been several studies of means of reducing $NO_x$ emissions from diesel engines (Refs. 3-35 through 3-38). The approaches studied included, individually and in combination, fuel injection rate and pattern variation, timing retard, turbocharging, exhaust gas recirculation (cold and hot), and water injection (into the intake manifold and cylinder). $NO_x$ emission reductions of 50 percent or more can be attained using these methods, but, as indicated in Table 3-22, in most cases the $NO_x$ reduction is accompanied by significant increases in CO emissions and smoke. In addition, in some cases, the associated fuel penalty is quite high and there are potential maintenance problems with the retrofitted emission control systems and/or the basic engine. The limited data and operating experience to date indicate that EGR (cold) is the most promising approach for reducing $NO_x$ emissions from diesel engines, but also dictate that additional testing and development are necessary.

### 3.4.4 Implementation of Retrofit Programs for Trucks

Many of the comments made previously in Sections 2.8.6 and 3.3 relative to the planning and implementation of I/M programs for heavy duty vehicles and of retrofit emission control programs for light duty vehicles are also relevant to the present discussion of the planning and implementation of a retrofit program for heavy duty vehicles (GVW > 6000 lb). In the interest of brevity, only the principal implementation considerations are delineated here. The implementation of such a program would involve the following steps and may require a time period of 1 to 2 years after the enabling legislation was passed.

Table 3-22. Summary of Diesel Engine Emission Reductions Using Various Retrofit Approaches (Ref. 3-38)

| Retrofit Approach | | Percent Reduction[a] | | | | | Potential Problems |
|---|---|---|---|---|---|---|---|
| Type | Description | $NO_x$ | HC | CO[b] | Smoke[c] | Fuel Economy | |
| Engine modification | Retard timing - 5° | 36 | 20 | -40 | -70 | 3 | -- |
| Engine modification | Retard timing - 10° | 52 | 40 | -70 | -150 | 8 | -- |
| EGR | Cold[d] - 7% | 25 to 50[e] | 0 | -10 to -50 | -100 | 1 | Corrosion and deposit buildup in EGR circuit |
| EGR | Cold[d] - 15% | 35 to 65 | 0 | -20 to -180 | -250 | 3 | Corrosion and deposit buildup in EGR circuit |
| Water injection[f] | 20% of fuel flow | 10 | NA[g] | NA | NA | NA | Corrosion and fouling of intake system |
| Water injection | 50% of fuel flow | 25 | NA | NA | NA | NA | Corrosion and fouling of intake system |

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[a] Based on the 13-mode engine cycle.

[b] Negative sign indicates an increase.

[c] Opacity

[d] Recirculated gases cooled to about 80°F; hot EGR results in significantly lower $NO_x$ reduction and greater fuel economy penalty.

[e] Range indicates half load to full load.

[f] Water injected into intake manifold.

[g] Data not available.

a. Promulgation of emission reduction, cost, and maintenance specifications for acceptability of retrofit devices/systems.

b. Development of the certification procedures to be followed by manufacturers of retrofit devices/systems.

c. Certification of garages and fleet mechanics to install retrofit devices/systems.

d. Development of procedures for filing certificates of compliance by vehicle and fleet owners.

e. Development of inspection procedures for checking the state of operation of in-use retrofit devices/systems on heavy duty vehicles.

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# 4. CONVERSION OF IN-USE VEHICLES FOR GASEOUS FUEL OPERATION

## 4.1 INTRODUCTION

The modification of in-use vehicles to permit their operation using gaseous fuels falls within the general definition of retrofit approaches discussed in Section 3. However, the feasibility of gaseous fuel conversion as an in-use vehicle emission control strategy depends not only on the availability, emission reduction effectiveness, and cost of the required hardware, but also on a number of other factors, such as the cost and availability of the gaseous fuel, the feasibility of providing the necessary fuel distribution system, and the impact of diverting the fuel from other uses. This is not a highly viable approach to the control of emissions from in-use vehicles in light of the availability problems presently being experienced with such gaseous fuels as propane and natural gas.

There are three basic types of gaseous fuel conversions that may be performed. These are (1) liquified petroleum gas (LPG), (2) compressed natural gas (CNG), and (3) liquified natural gas (LNG). Differences among the types manifest themselves principally in such areas as the type of conversion hardware required, conversion and fuel cost, and operating convenience (e.g., vehicle range). In addition to these three basic types of conversions, a distinction can be made between single-fuel conversions in which the vehicle is modified to operate exclusively on the gaseous fuel and dual-fuel conversions in which the modified vehicle is equipped to operate interchangably on either the gaseous fuel or gasoline.

## 4.2 DESCRIPTION OF GASEOUS FUEL SYSTEMS

Conversion of a gasoline-powered vehicle for operation on a gaseous fuel requires the installation of a new fuel tank designed to contain the alternative fuel, new fuel lines and appropriate control valves and regulators to ensure that the fuel reaches the engine at the required pressure and only when it is running, and a new carburetor designed to meter the flow of the gaseous fuel into the engine's induction system. Conversions for LPG and LNG also require the installation of liquid-gas converters that vaporize the fuel. In single-fuel systems, the above components replace the original fuel tank, fuel lines, fuel pump, and carburetor. In dual-fuel systems, the new components are in addition to the original system. A typical schematic diagram for dual-fuel operation with LPG and gasoline is shown in Figure 4-1. In addition to the new equipment that must be retrofitted to an in-use vehicle to permit its operation on a gaseous fuel, engine adjustments such as air/fuel ratio and ignition timing are required to achieve proper operation with the gaseous fuel. Optimization of engine adjustments is necessary if maximum emission reductions are to be achieved with minimum impact on vehicle performance and fuel economy. For vehicles not originally equipped with hardened valve seats, installation of such seats may also be necessary to prevent excessive wear.

A number of systems for conversion of light duty vehicles to gaseous fuel operation are currently available. The operational consequences of using gaseous fuels instead of gasoline result from the differences in the physical and thermodynamic properties of the fuels. A summary of pertinent properties for gasoline, LPG, CNG, and LNG is given in Table 4-1. For vehicle applications, the most important properties are the state (liquid or gas) of the fuel at ambient temperature and pressure, and its energy density (Btu/ft$^3$). These properties significantly affect the ease with which the fuel can be stored on board the vehicle and at distribution stations. Tankage requirements (weight and volume) and the corresponding vehicle range between fueling stops are shown in Table 4-2. The advantages of gasoline over the gaseous fuels in this regard are clearly indicated in Table 4-2.

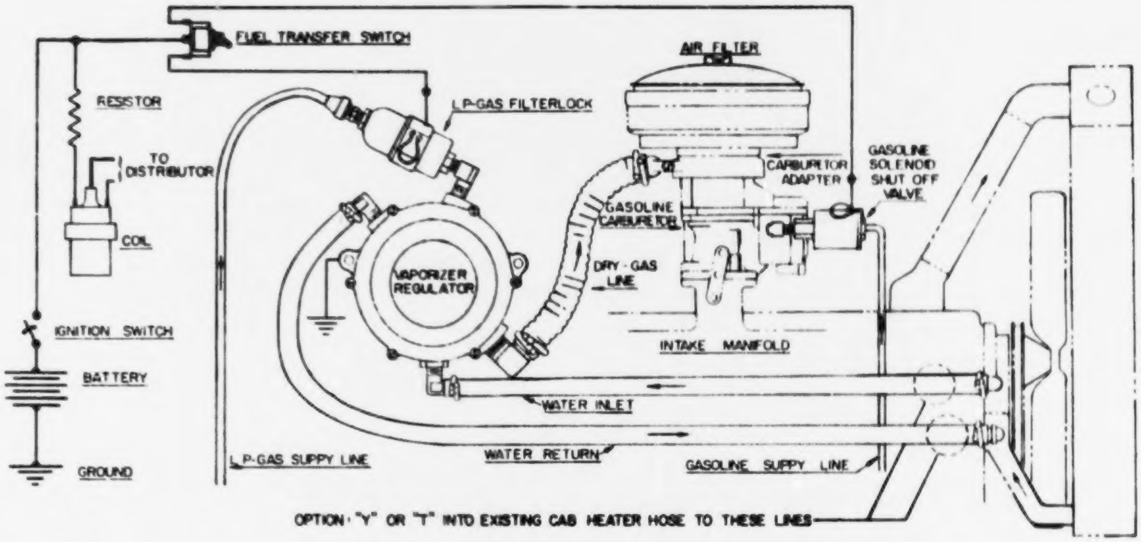
FUEL TRANSFER SWITCH
AIR FILTER
RESISTOR
LP-GAS FILTERLOCK
TO DISTRIBUTOR
CARBURETOR ADAPTER
GASOLINE SOLENOID SHUT OFF VALVE
GASOLINE CARBURETOR
COIL
VAPORIZER REGULATOR
DRY-GAS LINE
IGNITION SWITCH
INTAKE MANIFOLD
BATTERY
WATER INLET
LP-GAS SUPPY LINE
WATER RETURN
GASOLINE SUPPY LINE
GROUND
OPTION: "Y" OR "T" INTO EXISTING CAB HEATER HOSE TO THESE LINES

Figure 4-1. Schematic Diagram for Dual Fuel Operation with LPG and Gasoline (Ref. 4-3)

### Table 4-1. Properties of Gasoline and Gaseous Fuel Alternatives

| Property | Fuels | | | |
|---|---|---|---|---|
| | | | Methane | |
| | Gasoline | Propane (LPG) | Gas (CNG) | Liquid (LNG) |
| Chemical formula | $(CH_{1.85})_n$[a] | $C_3H_8$ | $CH_4$ | $CH_4$ |
| Normal boiling point (° F) | 100-400 | -44 | - | -260 |
| Storage temperature (° F) | ambient | ambient | ambient | -260 |
| Storage pressure (atm) | 1 | 15 | 200 | 2 |
| Heating value[b] | | | | |
| Btu/lb | 19,400 | 21,560 | 21,520 | 21,520 |
| Btu/gal[c] | 119,000 | 91,500 | 24,300 | 80,000 |
| Specific gravity | | | | |
| Liquid (water = 1) | 0.73 | 0.51 | - | 0.45 |
| Vapor (air = 1) | 3.3 | 1.52 | 105[c] | 0.52[c] |
| Octane number (RON) | 85[d] | 96 | 115 | - |
| Ignition temperature (° F) | 650 | 970 | 1170 | - |
| Flammability limits (% by volume) | 1-10 | 3-10 | 5-15 | - |
| Reference volume | 1 gal | 1 gal | 100 scf[e] | 1 gal |
| Gasoline equivalent for same energy (gal) | 1.0 | 0.78 | 0.20 | 0.67 |

[a] Approximate formulation; specific gasolines vary somewhat from this expression

[b] Lower heating value

[c] Fuel stored at pressure and temperature listed above.

[d] No additives (e.g., lead alkyls to increase the octane number).

[e] Standard cubic feet.

Table 4-2. Tankage and Range Comparisons

| Parameter | Fuels | | | |
|---|---|---|---|---|
| | Gasoline | Propane (LPG) | Methane | |
| | | | Gas (CNG) | Liquid (LNG) |
| Weight (lb) | | | | |
| Fuel alone | 122 | 85 | 22 | 75 |
| Fuel + tank | 137 | 162 | 142 | 162 |
| Volume ($ft^3$) | | | | |
| Fuel alone | 2.7 | 2.7 | 2.7 | 2.7 |
| Fuel + tank | 2.9 | 3.5 | 3.1 | 3.8 |
| Range (mi) | 300 | 230 | 60 | 200 |

Basis

20-gal fuel volume, assuming 15 mpg for gasoline.

## 4.3 EMISSION REDUCTIONS ATTAINABLE THROUGH GASEOUS FUEL CONVERSION

While a number of vehicles have been converted for operation on gaseous fuels, evaluation of the emission reductions obtained by these conversions has been limited. Most of the emissions tests have been done on single vehicles converted by a particular manufacturer as part of a gaseous fuel system development program or on a small fleet (usually less than 10 vehicles) of government-owned or leased vehicles. The emissions tests have been conducted mainly by the Environmental Protection Agency (EPA) (Ref. 4-1) and the California Air Resources Board (CARB)(Ref. 4-2). Most of the CARB data were obtained using the seven-mode test procedure [1970 Federal Test Procedure (FTP)], while EPA used the 1972-CVS FTP. In addition, the EPA tested a number of cars using both the 1970 and 1972 FTP (Ref. 4-1). Comparison of these two sets of data indicates that for gaseous fuel operation the two test procedures yield emission levels that are not greatly different. Hence, the two types of emission data were reviewed and assessed in a collective sense to draw conclusions concerning the effectivity of gaseous fuel conversions.

It may also be noted that most of the HC emissions data for gaseous fuel vehicles reported by the CARB incorporate scale factors that account for the reduced photochemical reactivity of the hydrocarbons in the gaseous fuel exhaust. Since EPA has not yet determined an appropriate basis for developing reactivity correction factors for this purpose, the scale factor was removed from the CARB data in compiling and reviewing the data on gaseous fuel exhaust emissions.

Analysis of the data discussed above indicates that a significant reduction in all three exhaust pollutants — hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides ($NO_x$) — can be obtained through a conversion from gasoline to gaseous fuel operation. Reductions as high as 60 percent for HC and $NO_x$ emissions and 90 percent for CO emissions have been obtained immediately following conversion to gaseous fuel when ignition timing and air/fuel ratio are optimized. The actual emissions benefit indicated by the data varies with a number of factors, including the type of conversion (LPG vs CNG/LNG) and the model year of the converted vehicle (post-1971 vs earlier models). Also, while the data show that the levels of CO emissions after conversion are consistently very low (often less than 5 gm/mi), the HC and $NO_x$ emissions vary over a wide range. Depending on the emission reductions desired, different tradeoffs may be made between emissions, fuel economy, and vehicle performance. Therefore, it is necessary in the evaluation of gaseous fuel conversion systems to have data on fuel economy and vehicle performance, as well as emission reductions. Also, the sensitivity of HC and $NO_x$ emissions to engine adjustments makes it adviseable to have a periodic emission inspection to insure that operators of gaseous-fueled vehicles do not alter the ignition timing and carburetor settings to improve fuel economy and performance at the expense of higher emissions.

The best attainable short-term (i.e., without deterioration) reductions that can be attained by gaseous fuel conversions when no consideration is given to fuel economy are presented in Table 4-3.

In general, it is to be expected that dual-fuel conversions will not be capable of achieving as large emission reductions as are possible using single-fuel conversions, since compromises are required in various engine adjustments to permit interchangable operation using both the gaseous fuel and gasoline.

Data on the deterioration of emissions from vehicles converted for gaseous fuel operation, as those vehicles accumulate time and mileage, are extremely limited, and it is not possible to project with any certainty what the trend will be.

Table 4-3. Emission Levels and Reductions Obtainable Through Single-Fuel Gaseous Conversion (Refs. 4-1 through 4-3)

| Applicable Model Years | Fuel | Emission Level (1975 FTP) | | | Percent Reduction From Gasoline Baseline | | |
|---|---|---|---|---|---|---|---|
| | | HC | CO | $NO_x$ | HC | CO | $NO_x$ |
| 1968-1971 | Gasoline (baseline) | 4.8 | 60.0 | 4.8 | | | |
| | LPG | 2.1 | 14.2 | 2.9 | 55 | 75 | 40 |
| | LNG/CNG | 1.7 | 5.1 | 1.4 | 65 | 90 | 70 |
| 1972-1974 | Gasoline (baseline) | 2.8 | 30.0 | 3.0 | | | |
| | LPG[a] | 1.5 | 2.7 | 1.1 | 45 | 90 | 60 |
| | LNG/CNG[a] | 1.0 | 2.0 | 0.7 | 60 | 95 | 70 |

[a] Best attainable, not the average, for 1972-1974 vehicles. In general, emission reductions achievable with dual-fuel systems will be less than those shown.

## 4.4 INITIAL AND OPERATING COSTS

In assessing the costs associated with gaseous fuel conversion, it is advantageous to consider the initial costs and the operating costs separately. The initial costs include the cost of the fuel conversion hardware (under the hood), the fuel tank, and the labor to install the system. The operating costs include the cost of fuel and maintenance. In the case of operating costs, it is only the incremental costs compared to operation with gasoline that are of interest.

The initial costs are summarized in Table 4-4. These values reflect data obtained from manufacturers and distributors, and represent costs as of March 1974. The tank sizes (volumes) cited in Table 4-4 are either those required to achieve a vehicle range comparable to that with gasoline or, as in the case of CNG, those that are customarily installed in automobiles by companies in the business.

Since the initial cost of converting a vehicle to gaseous fuel is quite high, it is advantageous if at least part of that cost can be offset by reduced fuel and maintenance costs. It is generally agreed (Ref. 4-4) that the maintenance costs (general repair, engine tune-ups, oil changes, etc.) using gaseous fuels are less than those for operation with gasoline. On this basis, it is considered reasonable to take credit for an estimated maintenance savings of 0.0025 dollars per mile (1/4 ¢/mi). There is less agreement in the literature concerning the cost of gaseous fuels and the fuel economy that can be expected by using them. Based on information provided in Refs. 4-5 and 4-6, and on contacts with several companies concerned with the establishment of gaseous fuel distribution centers, the fuel cost and fuel economy data given in Table 4-5 were ascertained. The fuel costs shown for natural gas, both CNG and LNG, are much higher than often used in some previous studies, especially by utilities companies. The cost of the distribution and dispensing of the fuel was neglected in these studies. As in the case of gasoline, this cost for natural gas is significant. The fuel costs given in Table 4-5 do not include either Federal or State taxes as it can be expected

Table 4-4. Initial Costs for Conversion to Gaseous Fuels[a]

| Fuel | Total Cost ($) | Fuel Conversion Hardware ($) | Fuel Tank ($) | Labor ($) |
|---|---|---|---|---|
| Gasoline | - | - | - (23 gal) | - |
| LPG | 650 | 280 | 230 (30 gal) | 140 |
| CNG | 870 | 280 | 450 (1000 scf) | 140 |
| LNG | 1020 | 280 | 600 (30 gal) | 140 |

[a] Costs as of March 1974 for converting a passenger car to single-fuel gaseous system.

Table 4-5. Fuel Cost and Fuel Economy Data for Gaseous Fuel Operation

| Fuel | Sales Unit | Unit Fuel Cost ($/unit)[a] | Fuel Economy (miles/unit)[b] | Fuel Cost ($/mile) |
|---|---|---|---|---|
| Gasoline (regular) | Gal | 0.33 | 13 | 0.025 |
| LPG | Gal | 0.28 | 10 | 0.028 |
| CNG | 100 scf | 0.20 | 10 | 0.020 |
| LNG | Gal | 0.28 | 9 | 0.031 |

[a] No Federal or State tax included, based on first quarter 1974 price levels.

[b] Btu/mi for gaseous fuel operation assumed to be equal to that for operation with gasoline.

that an equivalent tax will be applied to all the fuels. In calculating the fuel economy for each fuel, it has been assumed that the vehicle averaged 13 mpg for gasoline and that the Btu/mi used for gaseous fuel operation was equal to that required with gasoline. Except for CNG, it does not appear that the fuel costs per mile vary much from fuel to fuel. The main disadvantage of CNG is the reduced range resulting from the size and weight of the tanks needed to store gas at 2000 to 3000 psi.

## 4.5 COST EFFECTIVENESS OF EMISSION REDUCTION THROUGH CONVERSION TO GASEOUS FUELS

Cost effectiveness information for attaining low emissions from controlled vehicles (1968-1974) through conversion to gaseous fuels is summarized in Table 4-6. The cost effectiveness is expressed as dollars per pound of pollution eliminated ($/lb) using the same general techniques as outlined in Section 3.2.1.7. The format of Table 4-6 is the same as that used in Tables 3-10 through 3-12 in Section 3 so that a direct comparison can be made between the cost effectiveness of the gaseous fuel conversion systems and emission control retrofit devices for gasoline-fueled vehicles. In general, it is found that gaseous fuel conversion systems compare unfavorably in terms of cost effectiveness whether based on direct costs (initial cost and maintenance savings) or on total costs, including fuel savings, unless the unit cost of the gaseous fuel is much below that of gasoline. At the present time, this seems to be the case for CNG only, and that system has the disadvantage of a significantly reduced range (one-quarter to one-third that for gasoline) and limited commercial availability of the fuel. The dominant factors in assessing the cost effectiveness of gaseous fuel systems are the unit cost of the fuel and the fuel economy of the vehicle when using the gaseous fuel. In evaluating claims made for gaseous fuel systems, it is important to know what assumptions have been made concerning these factors and to be certain the values used are realistic.

## Table 4-6. Summary of Cost Effectiveness Information for Gaseous Fuel Conversion

| Fuel | Initial Cost ($) | Maintenance Savings ($)[a] | Unit Fuel Price ($)[b] | Fuel Savings ($)[c] | Emissions (gm/mi-1975 FTP) | | | Cost Effectiveness[d] ($/lb) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Initial Costs and Maintenance Savings | | | Initial Costs and Maintenance and Fuel Savings | | |
| | | | | | HC | CO | $NO_x$ | HC | CO | $NO_x$ | HC | CO | $NO_x$ |
| Controlled Vehicles (1968-1971) baseline emissions: HC = 4.8, CO = 60, $NO_x$ = 4.8 gm/mi | | | | | | | | | | | | | |
| LPG | 650 | 125 | 0.28/gal | -150 | 2.1 | 14.2 | 2.9 | 1.81 | 0.11 | 2.52 | 3.33 | 0.14 | 3.24 |
| CNG | 870 | 125 | 0.20/100 scf | 250 | 1.7 | 5.1 | 1.4 | 2.16 | 0.12 | 1.99 | 2.05 | 0.08 | 1.32 |
| LNG | 1020 | 125 | 0.28/gal | -300 | 1.7 | 5.1 | 1.4 | 2.6 | 0.15 | 2.39 | 3.95 | 0.22 | 2.61 |
| Controlled Vehicles (1972-1974) baseline emissions: HC = 2.8, CO = 30, $NO_x$ = 3 gm/mi | | | | | | | | | | | | | |
| LPG | 650 | 125 | 0.28/gal | -150 | 1.5 | 2.7 | 1.1 | 3.18 | 0.18 | 2.52 | 4.08 | 0.23 | 3.24 |
| CNG | 870 | 125 | 0.20/100 scf | 250 | 1.0 | 2.0 | 0.7 | 3.77 | 0.24 | 2.95 | 2.50 | 0.16 | 1.95 |
| LNG | 1020 | 125 | 0.28/gal | -300 | 1.0 | 2.0 | 0.7 | 4.5 | 0.29 | 3.53 | 6.83 | 0.44 | 5.34 |

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[a] Maintenance saving of 0.0025 $/mi for 50,000 miles.

[b] No Federal or State tax is included in the fuel costs.

[c] Fuel savings in 50,000 miles compared with operation with gasoline; negative sign means an increase in fuel costs.

[d] Lifetime of gaseous fuel conversion system is taken to be 50,000 miles.

## 4.6 OTHER ASPECTS OF GASEOUS FUEL CONVERSION

Other factors that influence the feasibility of gaseous fuel conversion approaches are the effects on vehicle performance and safety considerations. In general, experience with gaseous fuel conversion fleets has demonstrated that acceptable vehicle performance (though often reduced from that obtained with gasoline) can be obtained with gaseous fuels. While safety considerations have restricted the use of gaseous fuels in some areas (e.g., in tunnels), enough experience has been accumulated with fleets of gaseous fuel vehicles to demonstrate that the fuels, in general, can be used safely. Various aspects of safety related to the use of gaseous fuels in vehicles are discussed in Refs. 4-4, 4-5, and 4-7.

## 4.7 USEFULNESS OF GASEOUS FUEL CONVERSION AS AN IN-USE VEHICLE EMISSION CONTROL STRATEGY

In judging the usefulness of gaseous fuel conversion as an emission control strategy for in-use vehicles, the following factors must be considered: reductions in total vehicle population emissions achievable as a function of time by the conversion strategy, cost of implementing the strategy, and impact of the diversion of gaseous fuels for vehicle use on other fuel requirements, including possible increases in emissions from stationary sources through fuel switching.

Considerations of the cost of gaseous fuel conversions, the limited availability and cost of refueling facilities, and limitations on the availability of gaseous fuels in many areas have generally led to the conclusion that gaseous fuel conversion is most practical when applied to certain commercial fleets of vehicles. The overall effectiveness and cost of fleet conversion programs are estimated in Ref. 4-8 for two cases of interest: taxicab fleets in New York City and in Washington, D.C. The outcome of that analysis indicates that emission reductions expected to result from converting the pre-1975 model year taxicab fleets in those two cities to gaseous fuels would be relatively small compared with the potential of other emission control strategies for in-use vehicles and would be short lived.

In other analyses (Refs. 4-9 and 4-10), the overall emissions impact of diverting natural gas from electric power generation to powering commercial vehicles in New York City has been considered. It was determined that to operate all commercial vehicles in New York City on natural gas would require the diversion of approximately one-half of the quantity of that fuel used for electric power generation. Replacing this fuel by 1 percent sulfur fuel oil was estimated to produce an increase of emissions of sulfur oxides equivalent to approximately 6 percent of the total New York City emissions of that pollutant. This is an example of the type of pollutant control tradeoffs that need to be evaluated in regions where supplies of gaseous fuels are limited.

It should be mentioned that the future availability of LPG as an alternate fuel does not look encouraging for either the near term or the longer term. In the near term, the production of LPG is tied directly to the production rates at natural gas processing plants and gasoline refineries. Though the production of LPG is expected to continue to rise through the 1970's, the annual increase is expected to taper off to levels considerably below those experienced in the 1960's. This is expected in large part to be due to the use of more propane and butane in gasoline production to achieve higher octane ratings in gasolines with low lead or no lead content.

With regard to natural gas supplies, a decrease in the production of domestic natural gas is expected in the late 1970's and early 1980's, because the production of synthetic natural gas and the supply of Alaskan gas will not grow fast enough. Therefore, a larger amount of natural gas will have to be imported, with a possible impact on cost. Also, while the continued limited use of natural gas for automotive applications is not likely to be a critical factor in the U.S. natural gas energy use balance, a major shift toward increased automotive consumption rates could alter this balance so as to degrade critical supply/demand factors in other consuming sectors. These ramifications on fuel supply and availability must be carefully weighed in evaluating the relative merit of gaseous fuel conversion as a control strategy for in-use vehicles.

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